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Volume 2: Chapters 1-5

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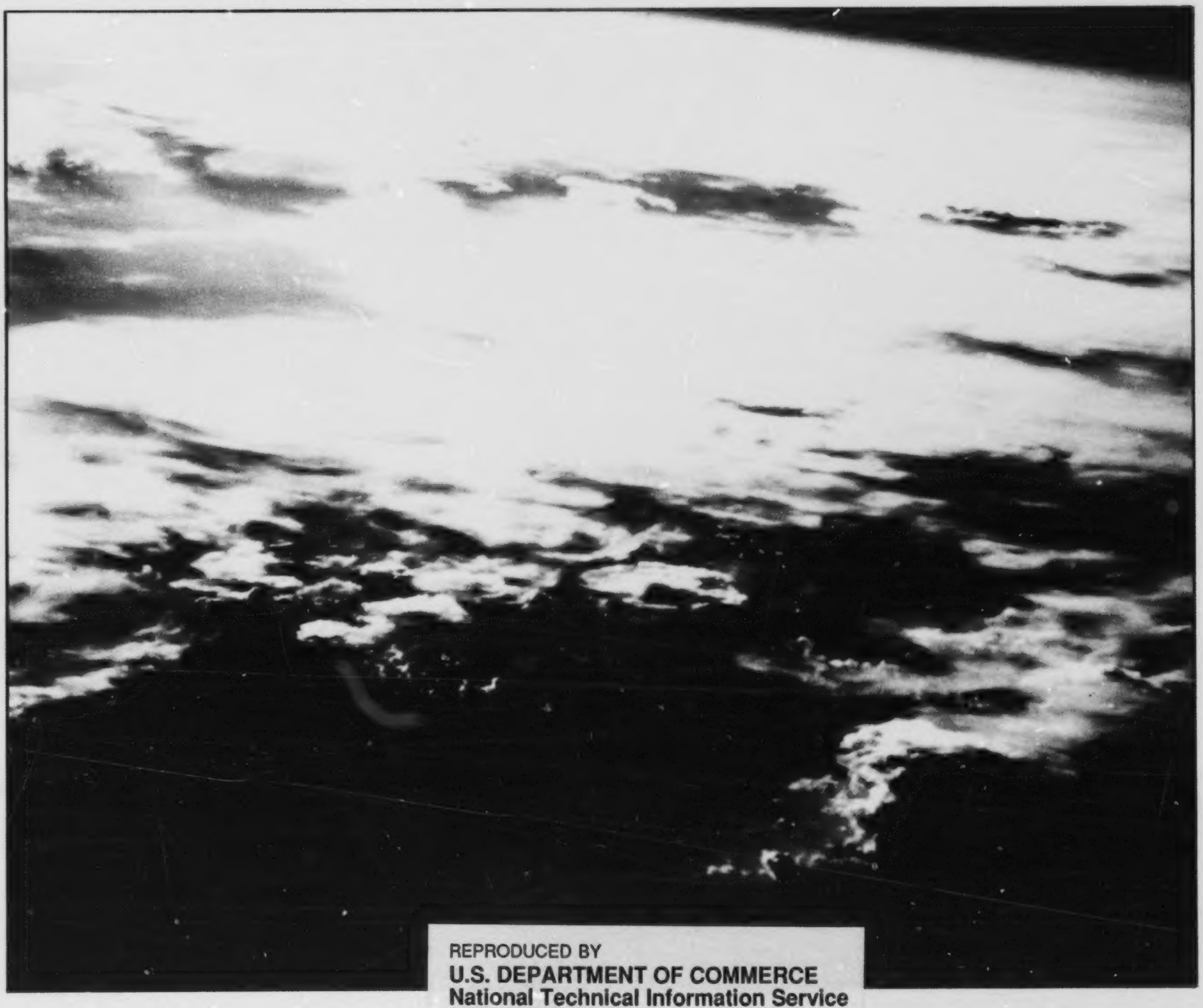

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INTRODUCTION

Ozone in the stratosphere helps protect humans, biological organisms, and useful materials from harm by partially blocking ultraviolet radiation in wavelengths from 295 nanometers to 320 nanometers (Ultraviolet-B; UVB) from reaching the earth's surface. The vertical distribution of ozone in the stratosphere and the relative dryness of that atmospheric region also play a role in sustaining the current radiative balance of the planet; changes in vertical distribution of ozone and stratospheric water vapor can influence the average surface temperature of the earth and its weather and climate. Because of these two roles, the composition and structure of the stratosphere are of human concern.

THE RISE OF CONCERN ABOUT STRATOSPHERIC CHANGE

In the early 1970s, Johnston and others expressed concern that the exhausts of the then proposed fleets of supersonic transports would deposit nitrogen oxides and water vapor into the stratosphere where these substances could decrease the abundance of ozone. In 1974, Rowland and Molina raised the concern that chlorofluorocarbons (CFCs), used as aerosol propellants, in foam blowing, as solvents, and as refrigerants, would pose a similar threat. Since then, others have raised concerns about nitrous oxides produced from combustion, soil processes, and fertilizers, about brominated compounds produced as fire extinguishing agents, and about a variety of other substances, including carbon dioxide (CO2) and methane (CH4), which have the potential to perturb stratospheric composition and structure.

An understanding of the role of infrared gases in maintaining earth's climate developed much earlier. In 1861 Tyndall discovered that water vapor absorbs infrared radiation. Not much attention was paid to infrared absorbing gases because they were assumed more or less constant in the atmosphere. In 1957, accurate measurements of CO2 started. Since then, concern about the rise in the atmospheric level of greenhouse gases and their potential to warm the earth and change its climate has steadily increased. In the last ten years, measurements of many radiatively important trace species other than CO2 have been made and have further heightened concern about global warming. In addition, recent studies have begun to consider how changes in the vertical location of ozone could add to, or in some cases subtract from, a greenhouse warming. As a result of these efforts, it has become clearer that considerations of stratospheric modification must include the potential contribution to the total greenhouse warming and the general circulation of weather on earth.

CONCERN ABOUT PUBLIC HEALTH AND WELFARE EFFECTS OF GLOBAL ATMOSPHERIC CHANGE

Concern about the effects of ozone depletion first focused on skin cancers, crops, and aquatic organisms during the Climate Impact Assessment Project in the 1970s. These concerns still exist and much has been learned about them since then. In addition a number of new concerns have been added, including the potential effect of UV radiation on materials useful to man, on ecosystems, on air pollution problems like ground-based oxidants and acid rain precursors, on the immune system of humans, and on cataracts and other eye problems. In fact, there has been a general recognition that ultraviolet radiation can alter many different kinds of "target" molecules and that changes at molecular levels could ultimately perturb the dynamics of the ecosystems. Despite advances, however, our understanding of the possible effects of increased ultraviolet radiation on the earth remains in its infancy.

Concern about the impacts of climate change, including sea level rise, alterations in hydrology and ecosystems, and a variety of other human endeavors has grown stronger since Revelle's famous statement that mankind is performing a great uncontrolled experiment on the earth. Knowledge of specific effects of climate change however, also remains rather limited.

NEED FOR ASSESSMENTS

Protection of the stratosphere is an environmental issue that differs from other concerns. Most environmental problems are local or regional in scale. Increases in ultraviolet radiation or changes in climate would produce effects worldwide. Most environmental problems can be eliminated as quickly as emissions can be reduced. For instance, the lifetime of particulates in the atmosphere can be measured in days. Once a problem is perceived and action decided upon, concentration will drop as quickly as reductions in source emissions can be made. For stratospheric modification this is not true. The lifetimes of many possible stratospheric perturbants are very long. If a problem begins to be observed, it will not disappear immediately, even if emissions are totally curtailed. In fact, even with a total termination of emissions of the long lived gases, decades to centuries would pass before concentrations declined to their original levels before humanity perturbed them. In the case of CFCs, if depletion starts to occur, actions that did not drastically curtail or reduce CFC and chlorine levels, in fact, would only tend to slow the rate of depletion.

These two features, the global impact of change, and the difficulty in preventing, slowing, or reversing change if it occurs, create a unique problem for scientists and decisionmakers attempting to assess risks of continued unrestrained emission of potential ozone modifiers. Errors may take decades or more to correct. Complicating the assessment process is that fact unlike many areas of risk assessment, experiments cannot be done to verify model predictions. There is no experimental earth to test theories and models -- the only experiment that can be done is the one now underway on the planet.

The Basis For This Assessment

Progress has been made, however, in the science of the stratosphere, the scientific disciplines related to effects, and in the process of doing risk assessments. Much has been learned since the Climate Impact Assessment Project (CIAP) done in the early 1970's and later assessments. Not only has there been a steady improvement in atmospheric science, but atmospheric science has reached out to other geophysical systems to include analysis of biogenic inputs into the atmosphere. During the past two years, under the leadership of Dr. Robert Watson and with the joint sponsorship of many international bodies, including the World Meterological Organization (WMO), the United Nations Environment Programme (UNEP), the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), the National Oceanic and Atmospheric Administration (NOAA), the Commission of European Communities, and the Bundesminsterium Fur Forschung and Technologie, the most comprehensive assessment of atmospheric science ever conducted has been completed. This review considered a wider range of issues, a greater number of scenarios of trace gases, and more uncertainties than in any previous assessment. The atmospheric chapters in this Risk Assessment draw heavily from that document and consequent documents developed by NASA from it.

Advances have also been made in health and welfare effects. In the field of melanoma, major advances have been made by Holman, Armstrong, Scotto, and Elwood. In materials, Androtti has significantly pushed the frontier forward. In tropospheric air pollution, Whitten has opened new paths. In climate, Hansen, Manabe, Washington, Ramanathan and others have greatly increased our understanding. In crops and aquatics, Teramura, Caldwell, Tevini, Hoder, Worrest and others have improved our understanding. In addition, the chapter on cataracts represents a new assessment extracted from a group coordinated by Morris Waxler of the Food and Drug Administration to understand that issue. This risk assessment attempts to build on the work of these and other scientists.

EXPLICIT INCORPORATION OF ECONOMICS AND THE INTEGRATION OF VARIOUS AREAS

The major way this assessment differs from prior assessments is that we explicitly look at emissions scenarios based on economics and we explicitly integrate consideration of production of trace gases, emissions, concentrations, atmospheric response, and effects to understand the joint implications of projected trends and system behavior through time. This approach has several advantages. It allows realistic assessment of risks rather than purely hypothetical cases such as "steady state emissions." It raises new scientific questions by forcing us to consider the inter-relationships of "disparate" disciplines. And it allows exploration of the joint implications of uncertainty in different areas. Only by integrating the various disciplines can we provide decision makers with a real understanding of the risks associated with emission of ozone-depleting substances and other trace gases that can modify the stratosphere.

CHAPTER 1

GOALS AND APPROACH OF THIS RISK ASSESSMENT

Under Part B of the Clean Air Act, the Administrator of EPA "shall propose regulations for the control of any substance, practice, process or activity (or any combination thereof) which in his judgment may reasonably be anticipated to affect the stratosphere, especially ozone in the stratosphere, if such effect in the stratosphere may be reasonably anticipated to endanger public health or welfare."

This risk assessment seeks to summarize the state of scientific knowledge so that the Administrator can make a considered judgment about the need for additional controls. Scientific evidence is therefore reviewed and evaluated for two purposes:

(1) to assess the likelihood that different human activities could alter the stratosphere in ways that altered ultraviolet radiation reaching earth's surface or that changed climate; and

(2) to assess the likelihood that changes in ultraviolet radiation or climate due to modifications in column ozone or stratospheric water vapor would have detrimental effects on human health or welfare.

ANALYTIC FRAMEWORK

There are four key parts to this risk assessment.

- Part 1 (Chapters 2, 3, 4) assesses possible changes in the composition of the atmosphere.
- Part 2 (Chapters 5, 6) assesses possible responses of the stratosphere to such changes in atmospheric composition.
- Part 3 (Chapters 7-16) assesses possible public health and welfare to changes in the stratosphere.
- Part 4 (Chapters 17, 18) assesses the joint implications of knowledge and uncertainties about atmospheric composition, stratospheric modification, and effects, to produce a range of outcomes consistent with current knowledge.

Appendix A presents a separate volume on assessing the risks that the incidence and mortality of melanoma will increase if stratospheric ozone levels are modified. Appendix B presents a separate volume on the effects of climate change. Every chapter tries to summarize the most likely science as well as the implications of uncertainty. A variety of cases and sensitivity analyses are analyzed and they examine how various uncertainties could affect the projection of changes. For example, in the integrating chapter, six scenarios are identified, encompassing the range of likely trajectories of emissions, not just the single best case growth estimate.

Each chapter begins with a summary description and then a set of general findings the latter of which is more detailed than the summary. Following this the relevant science is critically reviewed. The second to last chapter integrates all the findings from the previous chapters into a comprehensive modeling framework. The last chapter presents the joint implications of the prior work in terms of risk. In this way the risk assessment attempts to provide decisionmakers with a range of estimates of overall risk, based on various combinations of the joint uncertainties, not just a single estimate.

SUPPORTING DOCUMENTS AND ANALYSIS FOR THIS REVIEW

As mentioned earlier, this assessment draws heavily for atmospheric science from the WMO/UNEP assessment.[1] Other documents that were used include those produced by UNEP's Coordinating Committee on the Ozone Layer. In addition analyses from the Fluorocarbon Program Panel of the Chemical Manufacturers Association (CMA), which continues to fund research primarily related to atmospheric modeling, were used. The climate change conference convened by WMO in Villach, Austria in October 1985 also provided valuable information. Finally a risk assessment supervised by Dr. Donald G. Pitts and Morris Waxler of FDA is used for cataracts. All four documents should be consulted by those interested in more detailed treatments of these subjects.

CHAPTER OUTLINES

Chapter 2 focuses on past changes in stratospheric perturbants (trace gases that can change the structure and composition of the stratosphere). Chapter 3 reviews a variety of studies completed in the last two years on the future emissions of trace gases that are solely produced by man, and constitute potential ozone depleters. Chapter 4 centers on studies done to understand future concentrations of trace gases at least partly on biogenic sources -- carbon dioxide, methane, and nitrous oxide.

Following chapters on how atmospheric composition might change, Part II consists of Chapter 5 on stratospheric modification and Chapter 6 on climate change.

The next part of the analysis examines the effects of stratospheric modification on public health and welfare. In each chapter, the likelihood of effects are evaluated and attempts made to identify the quantitative relationships that relate atmospheric change to impact. Chapter 7 reviews basal and squamous skin cancers, and Chapter 8 melanoma. Chapter 9 addresses immune suppression and the diseases it might produce, Chapter 10 cataracts and other eye impairments. Chapter 11 analyzes possible crop and terrestrial ecosystem disruption, while Chapter 12 reviews potential damage to aquatic life. Chapter 13 covers materials damage while Chapter 14 completes the review of possible UV-B induced damage by examining possible air pollution effects of ozone modification. Chapter 15 then reviews possible effects of global warming on sea level rise and Chapter 16 summarizes Appendix B's review of the effects of global warming and associated climate change.

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[1] To the maximum degree possible this report directly used the results of other assessments. In many places large sections of text are taken from those reports. Such text has been put into **BOLDFACE**, to facilitate recognition of their quotation.

The next part of the Assessment consists of two chapters. Chapter 17 explains the models used to integrate the analyses, so that a comprehensive time dependent assessment of risks of stratospheric modification for conditions of uncertainty can be developed. Chapter 18 summarizes the risk assessment by presenting six scenarios of ozone depleting substances and estimates of possible damages for a variety of conditions with regard to atmospheric evolution and effects. Various emissions scenarios are used with different atmospheric models to estimate changes in ozone and global temperatures. These outputs of the atmospheric models are used in effects models that produce quantitative and qualitative estimates of impacts. In addition, extensive sensitivity analysis of the implications of many uncertainties is presented. The chapter integrates all that has proceeded.

Exhibit 1-1 summarizes the relationships among the various chapters.

EXHIBIT 1-1

Relationships Among the Chapters*

Emissions ——>	Atmospheric Response ——>	Effects ——>	The Range of Year-by-Year Impacts & Cumulative Impacts
o Chapter 1	o Chapter 5	o Chapter 7	o Chapter 18
o Chapter 2	o Chapter 6	o Chapter 8	
o Chapter 3		o Chapter 9	
o Chapter 4		o Chapter 10	
		o Chapter 11	
		o Chapter 12	
		o Chapter 13	
		o Chapter 14	
		o Chapter 15	
		o Chapter 16	

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* Chapter 17 develops model representations that integrate all components of the analysis.

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CHAPTER 2

STRATOSPHERIC PERTURBANTS: PAST CHANGES IN CONCENTRATIONS

SUMMARY

Recent measurements of trace gas abundance demonstrate that the concentrations of many trace gases are increasing throughout the lower atmosphere (the troposphere). These gases can directly influence the upper atmosphere (the stratosphere) when they are transported there and become involved in chemical reactions. Or they can play an indirect role in stratospheric issues by influencing the atmosphere's radiative balances (temperatures) or dynamics.

Tropospheric concentrations of the two most important chlorofluorocarbons (CFCs), CFC-11 and CFC-12, are growing at approximately 5 percent per year. In the last ten years, their concentrations have more than doubled. Tropospheric concentrations of other chlorine bearing perturbants are also growing. Measured increases in concentrations of chlorofluorocarbons include HCFC-22 at 11 percent per year and CFC-113 at 10 percent per year. Measured increases in chlorocarbons include carbon tetrachloride (CCl4) at 1 percent per year and methyl chloroform (CH3CCl3) at 7 percent per year.

Tropospheric concentrations of Halon-1211, a bromine bearing compound, are increasing at 23 percent per year. Trends in the concentrations of Halon-1301, another brominated compound, have not been reported.

Tropospheric concentrations of gases with some sources that are partially biogenic have also been increasing: nitrous oxide (N20) at 0.2 percent per year, carbon dioxide (CO2) at 0.4 percent per year, and methane (CH4) at 0.017 ppm per year.

Trace gases vary in their atmospheric residence times. Lifetimes of long-lived trace gases include 75 (+32/-17) years for CFC-11 and 111 years for CFC-12;[1] 90 years for CFC-113; 50 years for CCl4; 110 years for Halon-1301 and 25 years for Halon-1211; and 150 years for N2O. Lifetimes of shorter-lived trace gases include, for anthropogenic gases, 20 years for HCFC-22 and 6.5 years for CH3CCl3, and for the biogenic gas CH4, approximately 11 years.

After a gas is emitted, its fate depends on deposition processes, chemical interactions and transport to the stratosphere. Gases with long lifetimes are inert, being less influenced by chemical loss mechanisms and are thus more likely to survive until they can affect the stratosphere. Since the loss rate to the stratosphere is relatively slow, once concentrations of inert gases rise, their influence will be long lasting. If a given level of ozone depletion occurs, it will diminish slowly even if there are no new emissions. In fact, unless new emissions are less than the quantity of molecules lost to the stratosphere, concentrations and depletion would increase. The concentrations of gases that are chemically active are more dependent on a continued renewal by emissions. Thus their concentrations are subject to greater short term perturbation. The difference between long and short lifetimes has implications for the kinds of risks associated with rising concentrations of different trace species. Long lived gases will produce concentrations of those gases which may only be reversible over a period of decades or more.

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[1] The uncertainty associated with CFC-11 is +32 and -17 years; for CFC-12 it is +289 and -46 years. Thus for 100 kilograms of CFC-11 released in 1987, the best estimate is that 26 kilograms will still be in the atmosphere in 2087, with 66 percent probability that this amount will be reached between 2060 and 2119.

FINDINGS

1. MEASUREMENTS OF TROPOSPHERIC CONCENTRATIONS OF INDUSTRIALLY PRODUCED POTENTIAL OZONE-DEPLETING GASES SHOW SUBSTANTIAL INCREASES.

   1a. Measurements of current global average concentrations of CFC-11 are 200 parts per trillion volume (pptv), CFC-12 are 320 pptv, CFC-113 are 32 pptv, carbon tetrachloride (CCl_4) are 140 pptv, and methyl chloroform (CH_3CCl_3) are 120 pptv.

   1b. Based on measurements from a global monitoring network, worldwide concentrations of chlorine-bearing perturbants (i.e., potential ozone depleters) have been growing annually in recent years at the following rates: CFC-11 and CFC-12 at 5 percent; CFC-22 ($CHClF_2$) at 11 percent; CFC-113 at 10 percent; carbon tetrachloride (CCl_4) at 1 percent; and methyl chloroform at 7 percent.

   1c. Limited measurements show that global tropospheric concentrations of Halon 1211, a bromochlorofluorocarbon containing both chlorine and bromine (which is potentially more effective at depleting ozone), have been growing recently at 23 percent annually. Concentrations have been measured as one pptv.

   1d. Measurements of tropospheric concentrations of Halon 1301, another brominated compound that is a potential ozone depleter, estimate that concentrations are approximately one pptv. No trend estimates have been published.

2. ALMOST ALL EMISSIONS OF CFC-11, -12, -113, HALON 1211, AND HALON 1301 PERSIST IN THE TROPOSPHERE WITHOUT CHEMICAL TRANSFORMATION OR PHYSICAL DEPOSITION. AS A RESULT, MOST OF THESE EMISSIONS WILL EVENTUALLY BE TRANSPORTED TO THE STRATOSPHERE.

   2a. Gases which are photochemically inert accumulate in the lower atmosphere. Their emissions migrate to the stratosphere slowly. Estimates of their atmospheric lifetimes (generally calculated based on the time when 37 percent of the compound still remains in the atmosphere) are the following: CFC-11 is 75 years (107/58 years); CFC-12 is 111 years (400/55 years); CFC-113 is 90 years; CCl_4 is 50 years; Halon 1211 is 25 years; N_2O is 150 years; and Halon 1301 is 110 years. (Where provided, the range in parentheses shows one standard deviation).

   2b. Because of their long atmospheric lifetimes, the concentrations of these gases are currently far from steady state and will increase over time unless there is a large reduction in future emissions.

   2c. Because of their long atmospheric lifetimes, these gases would continue to contribute to possible future ozone depletion and climate change (CFCs and other gases affecting ozone are also greenhouse gases) long after they are emitted. Full recovery from any depletion or climate change would take decades to centuries.

MEASURED INCREASES IN TROPOSPHERIC CONCENTRATIONS OF POTENTIAL OZONE DEPLETERS

The tropospheric concentrations of many potential ozone-depleting trace gases have been measured as increasing throughout the world. Due to the strength of global circulation and the chemical stability of many of these gases, they are rapidly well mixed in the troposphere. Gases with longer lifetimes are more equally mixed between the Northern and Southern Hemispheres. The longest-lived trace gas, N2O, has the smallest interhemispheric mixing ratio: 1.003; and CH3CCl3, a gas with a short lifetime, has the greatest interhemispheric ratio: 1.37 (Prinn et al. 1983). After ozone depleters are transported to the stratosphere, they are photodissociated. The NOx, Clx, or Brx released can then enter into catalytic cycles that would reduce stratospheric ozone (see Chapter 5).

CFC-11

The global average concentration of CFC-11 (CFCl3) is approximately 200 parts per trillion volume (pptv) (Prinn et al. 1983). Tropospheric concentrations show little latitudinal variation, with a North/South interhemispheric mixing ratio of 1.09 (Prinn et al. 1983). CFC-11 has been measured at the five globally distributed sites of the Atmospheric Lifetime Experiment program. Average tropospheric concentrations are increasing at approximately 5 percent per year (WMO 1986). (Exhibit 2-1) In the last 10 years tropospheric concentrations have more than doubled (Rasmussen and Khalil 1986).

CFC-12

The global average concentration of CFC-12 (CF2CL2) is approximately 320 pptv and is increasing at approximately 5 percent per year (WMO 1986). It has been measured at the five Atmospheric Lifetime Experiment stations (Exhibit 2-2). Concentrations are globally well mixed, with a North/South interhemispheric mixing ratio of 1.08 (Prinn et al. 1983). In the last ten years tropospheric concentrations have more than doubled (Rasmussen and Khalil 1986).

HCFC-22

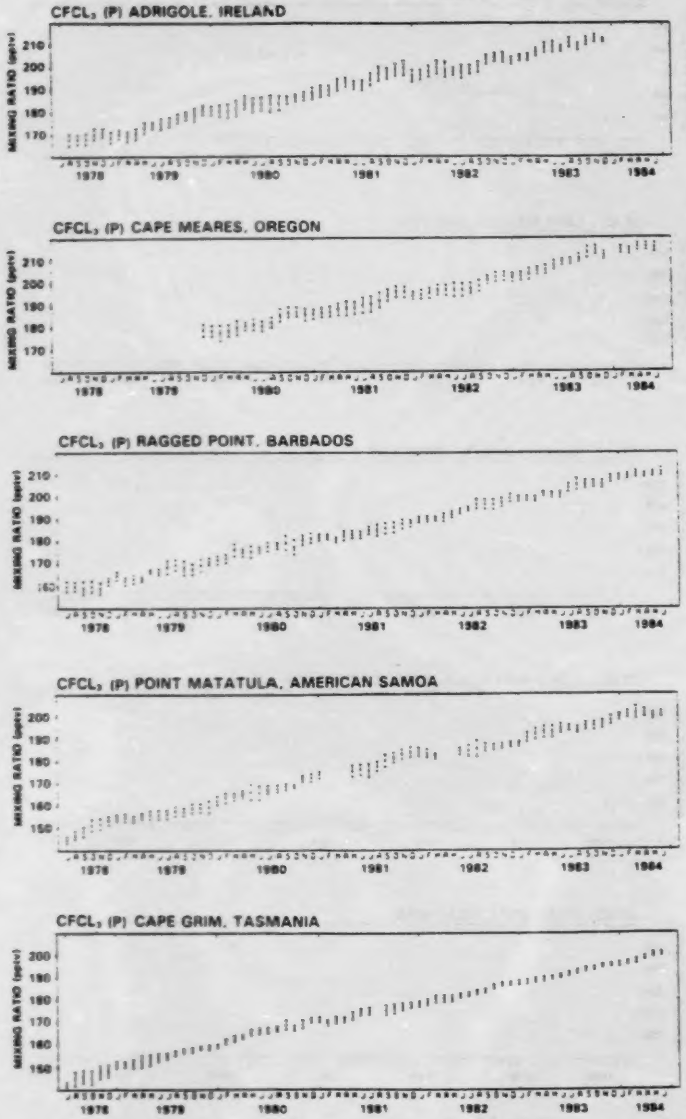
The global average concentration of HCFC-22 (CHClF2) is approximately 52 pptv (NAS 1984). Concentrations have been measured in the Pacific Northwest and at the South Pole. Global increases in tropospheric HCFC-22 concentrations have averaged approximately 11.7 percent per year (Khalil and Rasmussen 1982) (Exhibit 2-3).

CFC-113

The global average concentration of CFC-113 (C2Cl3F3) is approximately 32 pptv (NAS 1984). Recent increases in tropospheric CFC-113 concentrations, measured at the South Pole and Pacific Northwest, have averaged approximately ten percent per year (Rasmussen and Khalil 1982) (Exhibit 2-4).

EXHIBIT 2-1

Measured Increases in Tropospheric Concentrations of CFC-11 (CFCl3)

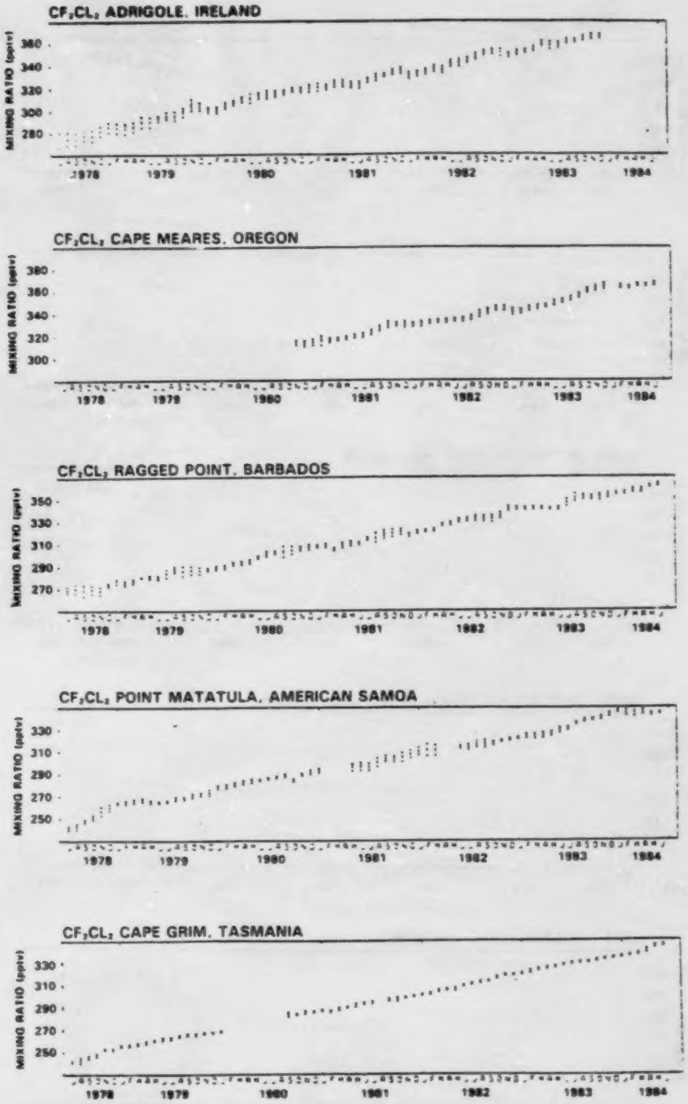


Average concentrations of CFC-11 are increasing at approximately five percent per year. Data are from the Atmospheric Lifetime Experiment.

Source: World Meteorological Organization, 1986; Figure 3-2.

EXHIBIT 2-2

Measured Increases in Tropospheric Concentrations of CFC-12 (CF2CL2)

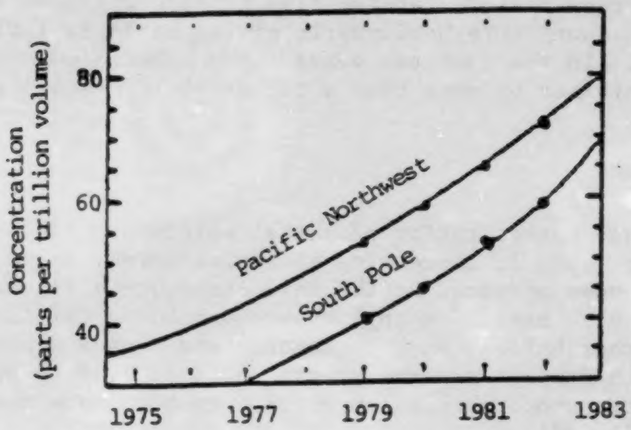


Average concentrations of CFC-12 are increasing at approximately five percent per year. Data are from the Atmospheric Lifetime Experiment.

Source: World Meteorological Organization, 1986; Figure 3-3.

EXHIBIT 2-3

Measured Increases in Tropospheric Concentrations of HCFC-22 (CHCIF2)

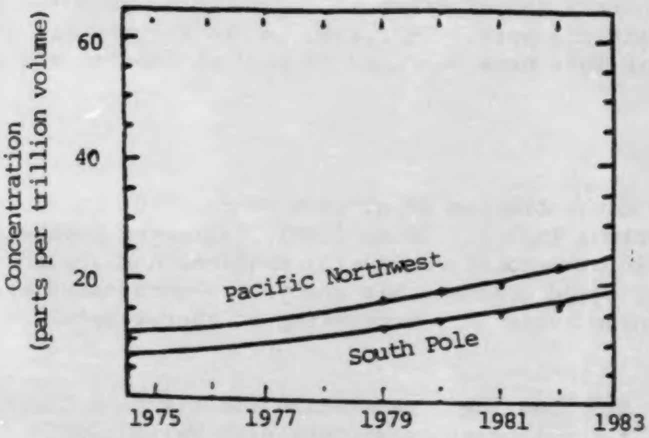


Average concentrations of HCFC-22 are increasing at approximately 12 percent per year.

Source: Rasmussen and Khalil 1982.

EXHIBIT 2-4

Measured Increases in Tropospheric Concentrations of CFC-113 (C2CL3F3)



Average concentrations of CFC-113 are increasing at approximately 10 percent per year.

Source: Rasmussen and Khalil 1982.

Carbon Tetrachloride

The global average concentration of carbon tetrachloride (CCl_4) is approximately 140 pptv and is increasing at approximately one percent per year (WMO 1986). It has been measured at the five Atmospheric Lifetime Experiment stations. The North/South interhemispheric mixing ratio is 1.05 (Prinn et al. 1983) (Exhibit 2-5). In the last ten years, tropospheric concentrations in both hemispheres have increased by more than a factor of 1.2 (Rasmussen and Khalil 1986) (Exhibit 2-5).

Methyl Chloroform

The global average concentration of methyl chloroform (CH_3CCl_3) is approximately 120 pptv and is increasing at approximately seven percent per year (WMO 1986). It has been measured at the five Atmospheric Lifetime Experiment stations (Exhibit 2-6). Because methyl chloroform has a relatively shorter lifetime than the other halocarbons, concentrations show a greater geographic variation. The North/South interhemispheric ratio is 1.37 (Prinn et al. 1983). In the last ten years, tropospheric concentrations have more than doubled (Rasmussen and Khalil 1986).

Halon-1301

The current concentration of Halon-1301 (CF_3Br), measured at the South Pole, is approximately one pptv (Khalil and Rasmussen 1985). Because researchers have only recently attempted to measure its concentration, no trend estimates are available. Archived air exists, however, and it may be possible to use it to establish trends for this species.

Halon-1211

The current concentration of Halon-1211 (CF_2ClBr), measured at the South Pole, is approximately one pptv. Increases in the tropospheric concentrations measured at the South Pole have averaged 23 percent (Khalil and Rasmussen 1985) (Exhibit 2-7).

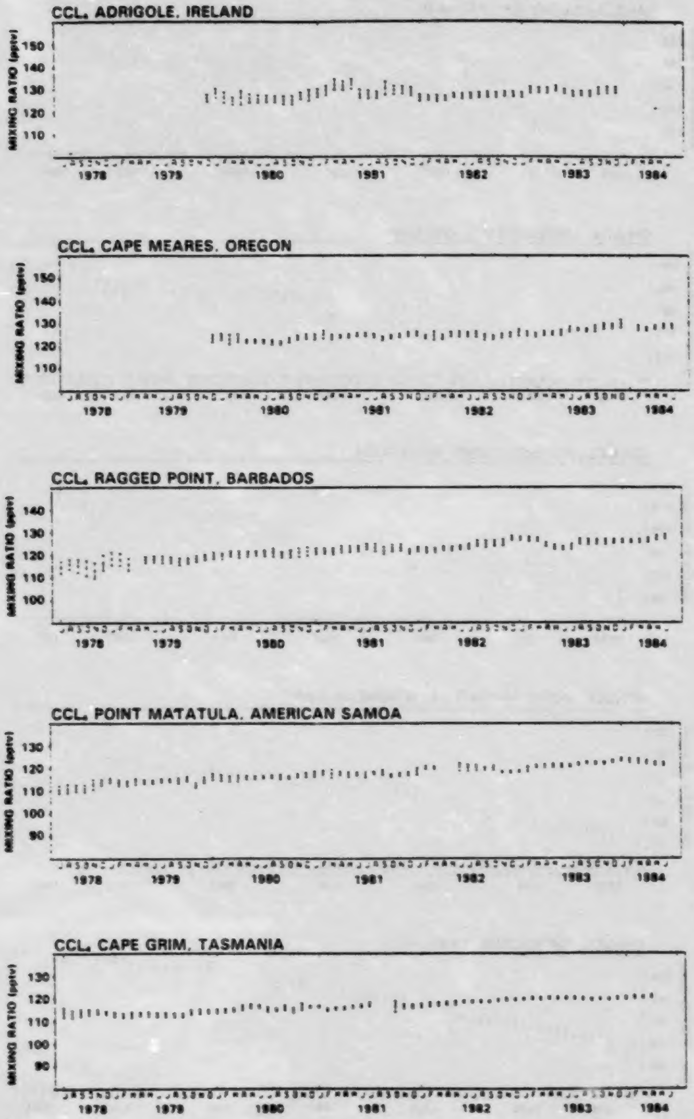
Nitrous Oxide

The mean global concentration of nitrous oxide (N_2O) is approximately 300 parts per billion volume (ppbv). Weiss (1981) collected separate measurements between 1976 and 1980 at several monitoring stations and aboard oceanographic vessels in the major world oceans. His analysis demonstrated that the tropospheric N_2O concentration was increasing at approximately 0.2 percent per year (Exhibit 2-8).

Recent data for N_2O from the five Atmospheric Lifetime Experiment stations are shown below. The results are consistent with Weiss (1981). The measured trends at the five network stations were: 0.77, 0.27, 0.24, 0.09, and 0.18 percent (WMO 1986). While the rates of increase appear to be larger in the northern hemisphere (0.25-0.7 percent per year) than in the southern hemisphere (0.1-0.2 percent per year) (WMO 1986), there is little variation in actual

EXHIBIT 2-5

Measured Increases in Tropospheric Concentrations of Carbon Tetrachloride (CCl4)

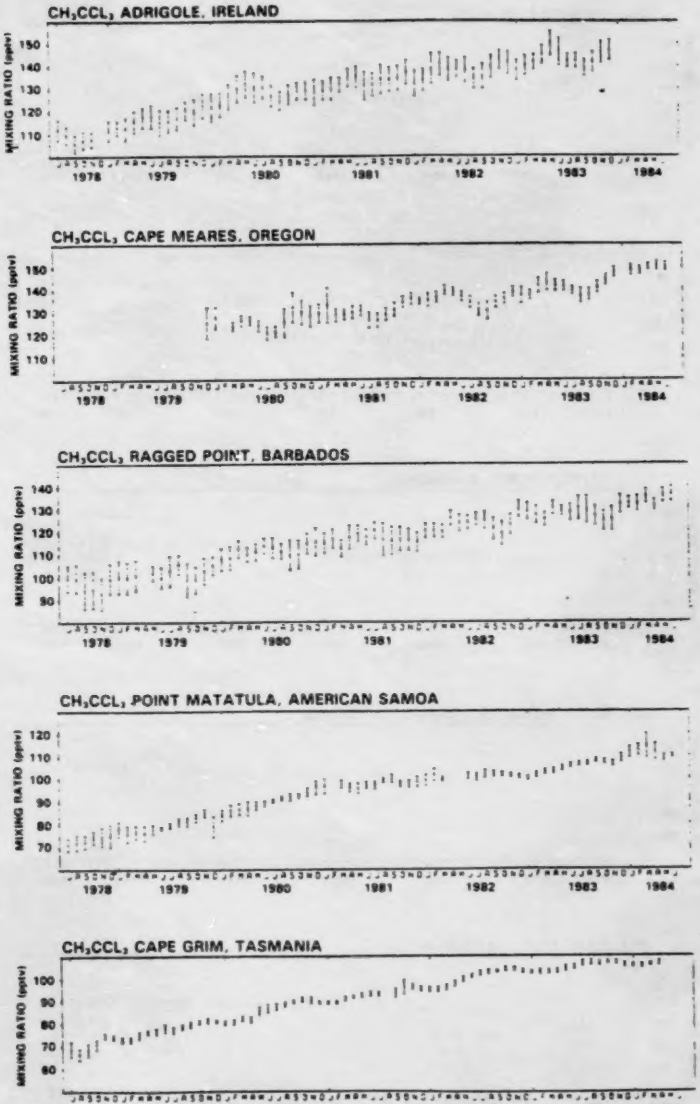


Average concentrations of carbon tetrachloride are increasing at approximately one percent per year. Data are from the Atmospheric Lifetime Experiment.

Source: World Meteorological Organization, 1986; Figure 3-5.

EXHIBIT 2-6

Measured Increases in Tropospheric Concentrations of Methyl Chloroform (CH3CC13)

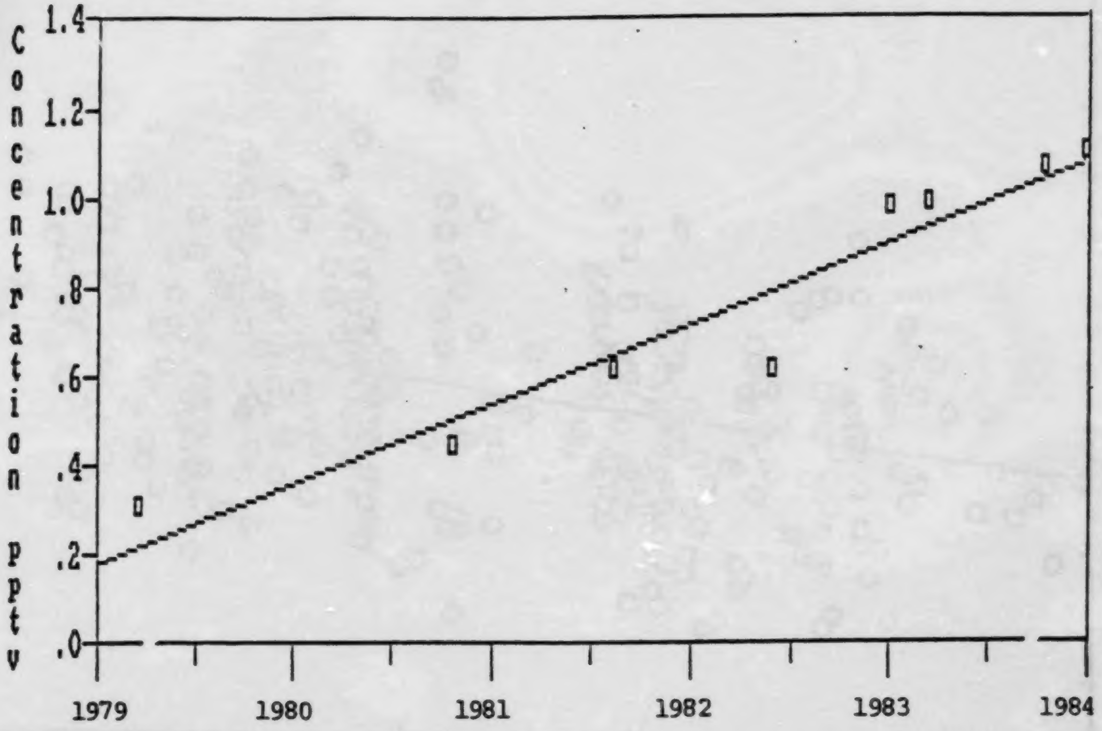


Average concentrations of methyl chloroform are increasing at approximately seven percent per year. Data are from the Atmospheric Lifetime Experiment.

Source: World Meteorological Organization, 1986; Figure 3-4.

EXHIBIT 2-7

Measured Increases in Tropospheric Concentrations of Halon-1211 (CF2ClBr)

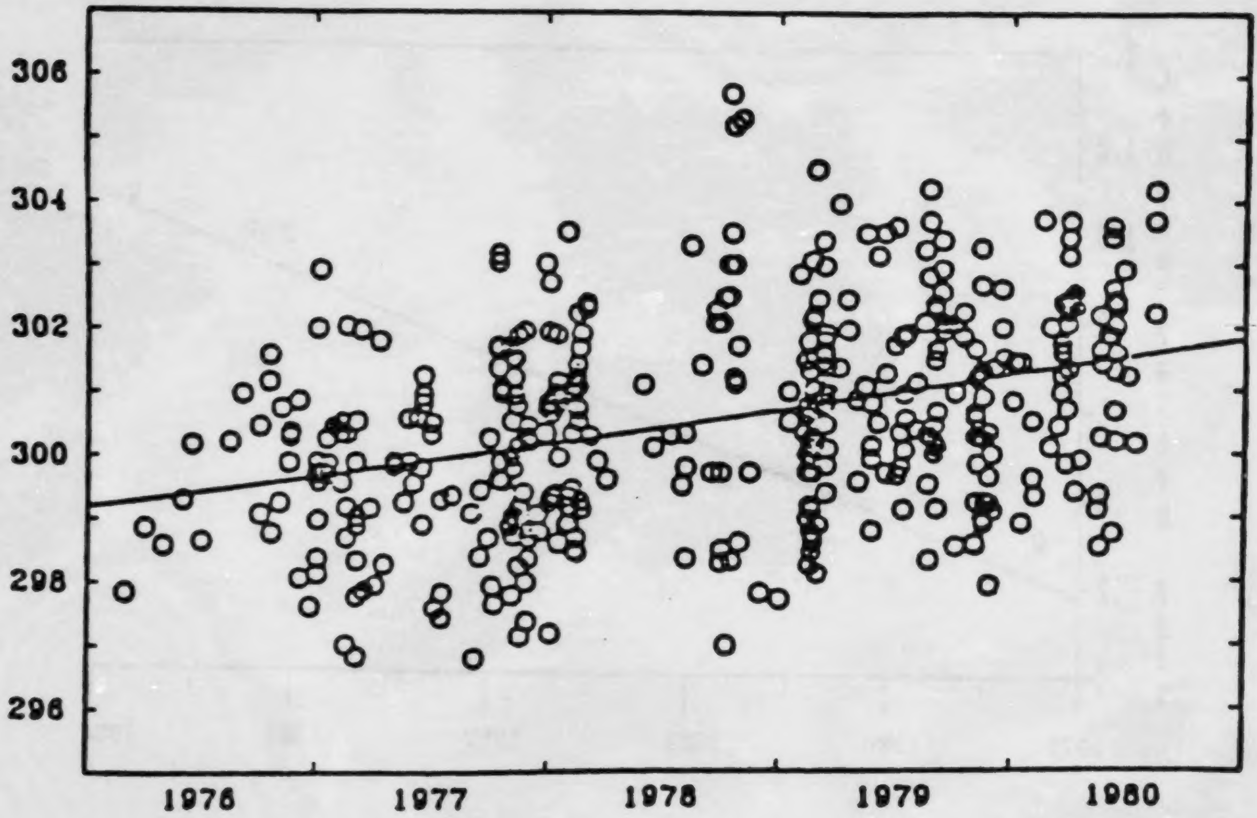


Measurements from South Pole. Average concentrations of Halon-1211 are increasing at approximately 23 percent per year.

Source: Khalil and Rasmussen, 1985.

EXHIBIT 2-8

Measured Increases in Tropospheric Concentrations of Nitrous Oxide (N2O)



Measurements of tropospheric nitrous oxide concentrations. Data were collected at several monitoring sites and aboard vessels in the major world oceans. Concentrations are increasing at approximately 0.2 percent per year.

Source: Weiss, 1981.

concentrations. The North/South interhemispheric mixing ratio is 1.003 (Prinn et al. 1983). If statistically significant, this discrepancy may be due to a growing imbalance between Northern sources and global sinks (WMO 1986) (Exhibit 2-9).

Pearman et al. (1986) measured N2O concentrations trapped in polar ice and provided the first evidence of changing N2O concentrations over hundreds of years. They found that "the ice data for recent times agree with modern measurements" and that concentrations have increased by 6 ppbv per 100 years over the last three centuries. They conclude that their recent trend estimate of 0.5-1.8 ppbv per year is not characteristic of the 400-year ice record, but results from an increase since the time of the Industrial Revolution (Exhibit 2-10).

MEASURED INCREASES IN TROPOSPHERIC CONCENTRATIONS OF POTENTIAL OZONE INCREASERS

Carbon dioxide (CO2) and methane (CH4) may, in some cases, contribute to increasing ozone abundance in the stratosphere (CO2 and CH4) or in the troposphere (CH4). They may also contribute to global warming. Atmospheric measurements indicate that their concentrations of potential ozone increasers are increasing.

Carbon Dioxide

Continuous and accurate measurements of CO2 concentrations began in 1958 at Mauna Loa Observatory in Hawaii (Keeling and GMCC/NOAA). The data show an increase of approximately ten percent since then (Exhibit 2-11).

Other measurements of the rise of CO2 have been made and are consistent with the Mauna Loa time series, each varying in seasonal amplitude depending on the distance from annual biospheric sources (Keeling 1978; Keeling et al. 1976; Peterson et al. 1982; and Sundquist and Broecker 1985).

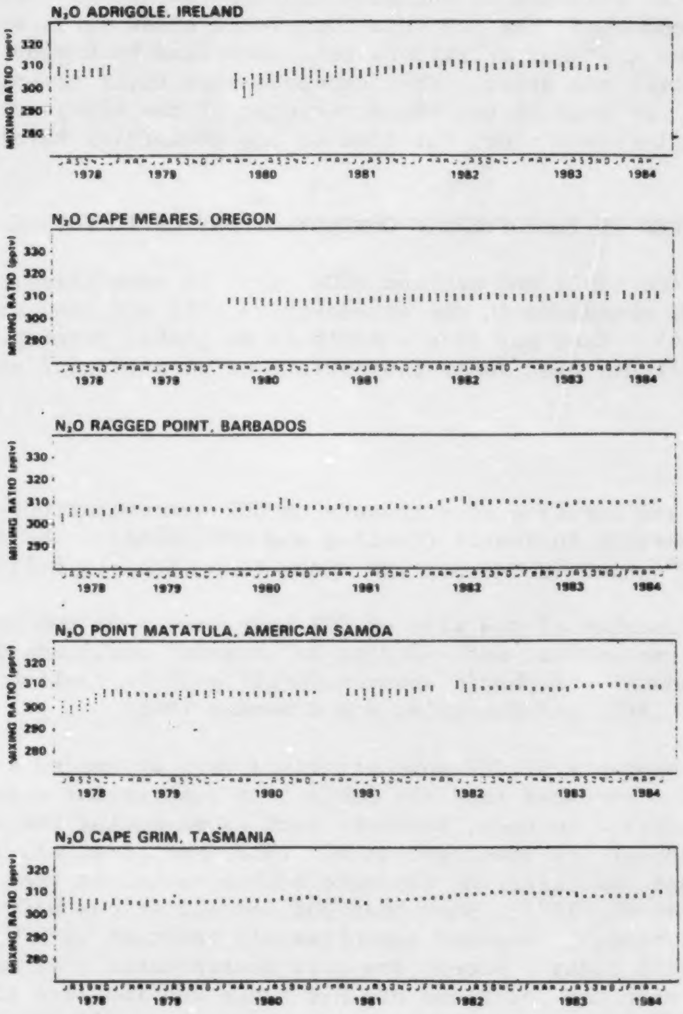
Direct measurements of CO2 concentrations were attempted as early as 1872 (Callendar 1958). Because they are subject to substantial error, their utility is limited. Indirect methods, however, such as measuring the concentrations of CO2 trapped in polar ice (Oeschger et al. 1982; Neftel et al. 1982; and Delmas et al. 1980), and analyzing the isotopic carbon ratios in tree rings (Freyer 1978; and Peng et al. 1983), show that CO2 concentrations before 1850 (pre-industrial times), remained approximately constant at 270 ppm ± 10 -- 25 percent lower than today. Recent ice core measurements (Pearman et al. 1986) are consistent with the upper end of this range and indicate that as early as the seventeenth and eighteenth centuries, the average CO2 concentration was approximately 281 ppm ± 7 ppm (Exhibit 2-12).

Methane

Ambient atmospheric measurements in the last several decades show that the concentration of methane is increasing (Rasmussen and Khalil 1984; Blake et. al. 1982; Fraser, Khalil and Rasmussen, 1984; Fraser et. al. 1981; and Ehhalt, Zander, and Lamontague 1983). Estimates of the rate of increase vary.

EXHIBIT 2-9

Measured Increases in Tropospheric Concentrations of Nitrous Oxide (N20)

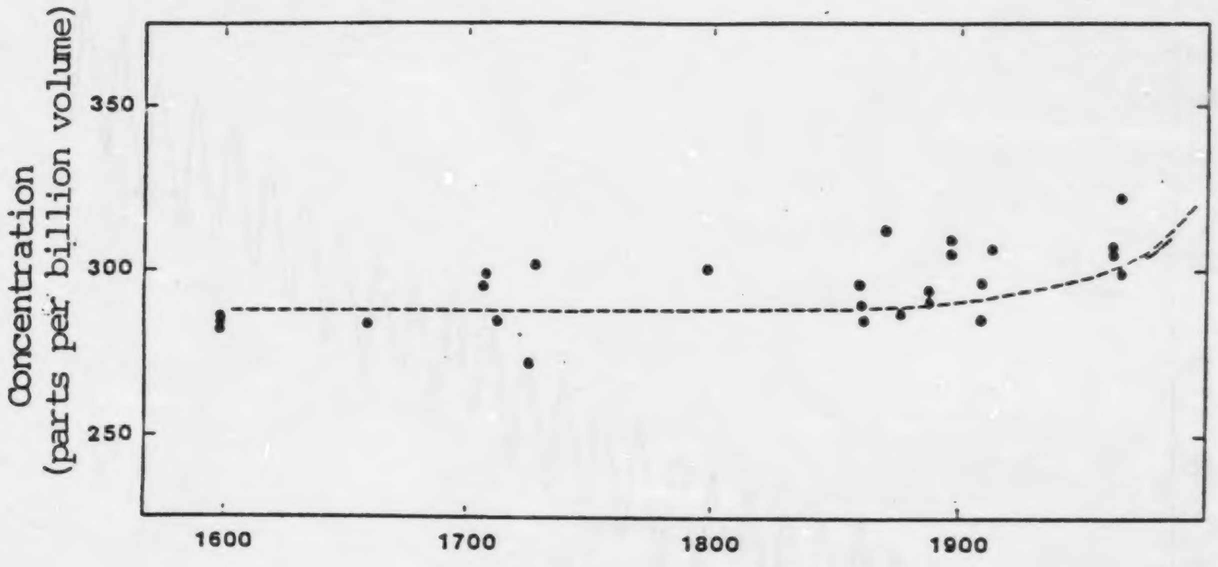


Rates of increase in tropospheric nitrous oxide at the five monitoring stations above are: 0.77%, 0.27%. 0.24%, 0.09%, and 0.18%. While the rates of increase appear to be larger in the Northern hemisphere than in the southern hemisphere, there is little variation in actual concentrations. Data are from the Atmospheric Lifetime Experiment.

Source: World Meteorological Organization, 1986; Figure 3-7.

EXHIBIT 2-10

Ice Core Measurements
Nitrous Oxide (N2O) Concentrations

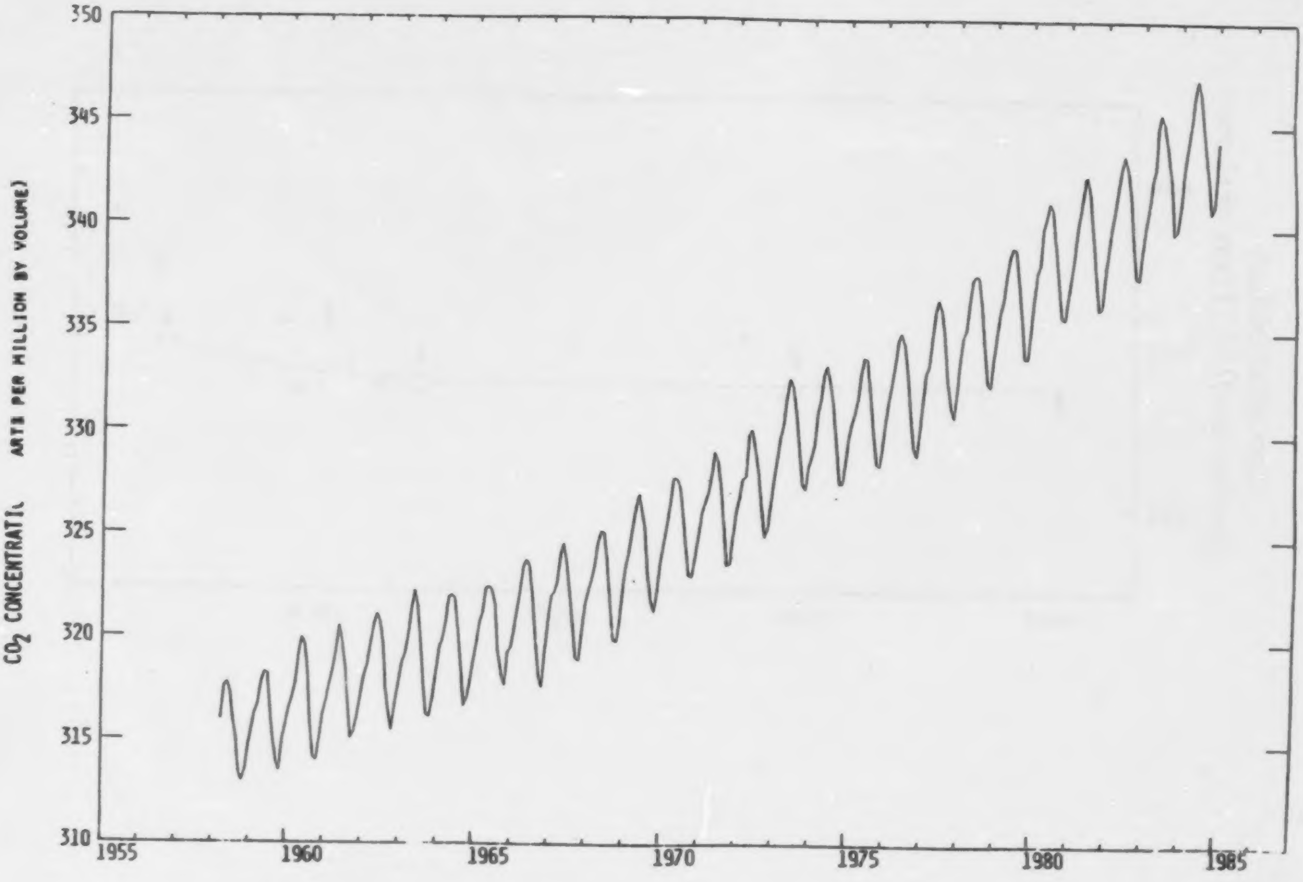


Ice core data show that nitrous oxide concentrations were relatively constant until the time of the Industrial Revolution.

Source: Pearman et al., 1986.

EXHIBIT 2-11

Measured Increases in Tropospheric Concentrations of Carbon Dioxide (CO2)

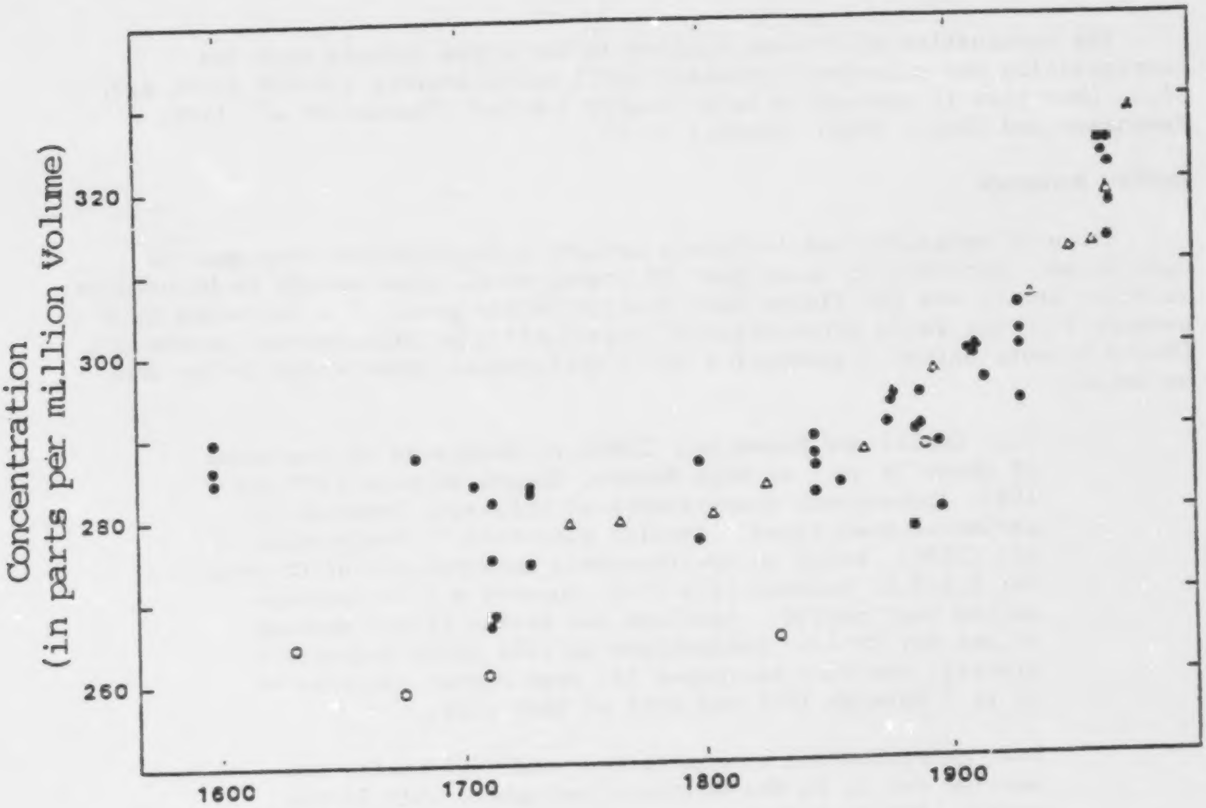


Monthly measurements from Mauna Loa, Hawaii. Data collection began in 1958 with the International Geophysical Year. Since that time, concentrations have increased 10 percent.

Source: Keeling, C.D., and GMCC/NOAA, unpublished.

EXHIBIT 2-12

Ice Core Measurements of Historical Carbon Dioxide (CO2) Concentrations



Ice core data show that carbon dioxide concentrations were relatively constant until the time of the Industrial Revolution.

Source: Adopted from Pearman et al., 1986.

Rasmussen and Khalil (1984) had computed an average annual increase of 1.3 percent, which at current concentrations is an increase of 0.02 ppm per year. Their recent work (Khalil and Rasmussen 1986), however, indicates that this trend estimate was influenced by interannual variability which may be linked to the effects of the El Nino-Southern Oscillation. Their corrected estimate of the long-term rate of increase is about 0.016 ppm per year, or one percent annually. Measurements of Blake et. al. (1982) are consistent with a linear rise of 0.018 ppm per year. Recently, spectrographic analyses by Rinsland, Levine and Miles (1985) indicate an annual growth rate since 1951 of 1.10 percent. Rowland (in NASA 1986) shows an increase of 0.017 ppm per year since 1977 (Exhibit 2-13).

The examination of methane trapped in ice cores reveals that its concentration was relatively constant until approximately 150-200 years ago. Since that time it appears to have roughly doubled (Pearman et al. 1986; Rasmussen and Khalil 1984) (Exhibit 2-14).

Carbon Monoxide

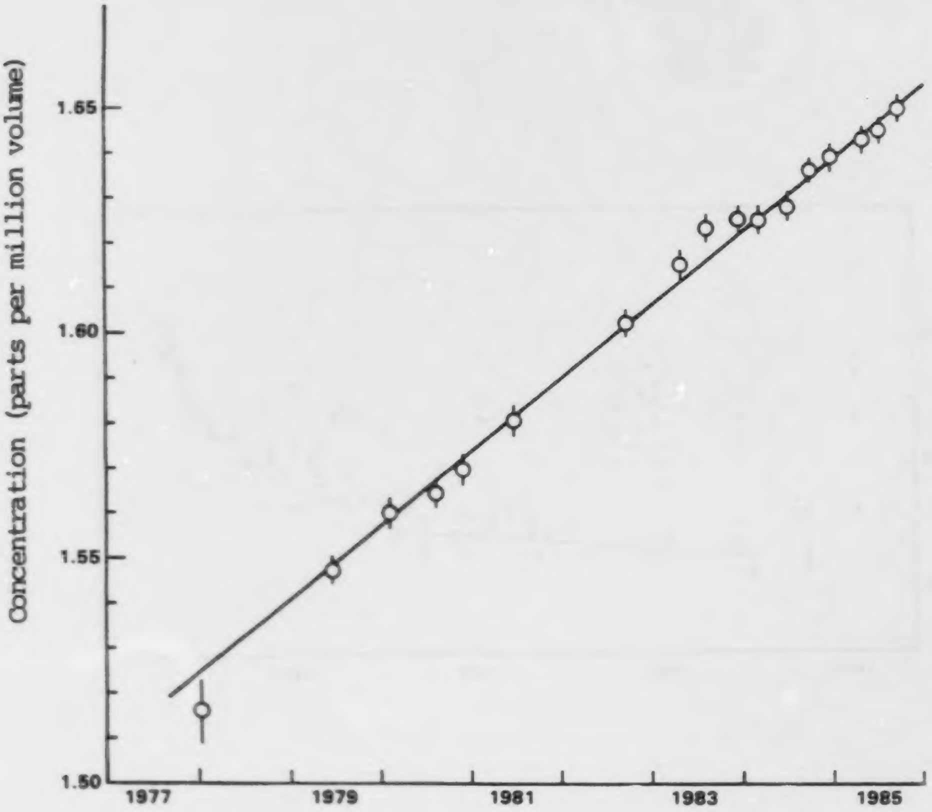
Since CO emissions can influence methane concentrations they must be considered. Information about past CO trends would allow models to be used to estimate how CO and CH4 fluxes have changed in the past. The following is a summary from the World Meteorological Organization's international assessment (World Meteorological Organization 1986) (references cited refer to the WMO document):

> [... Khalil and Rasmussen (1984b,c) indicated CO increases of about 5% yr^{-1} at Cape Meares, Oregon between 1979 and 1982. Subsequent measurements at this site lowered the estimated mean trend. Results presented by Dvoryashina et al. (1984), based on spectroscopic measurements of CO over the U.S.S.R. between 1971-1983, suggest a 1-2% increase during that period. Rinsland and Levine (1985) deduced values for CO over Switzerland in 1951 (from Migeotte's plates), and they estimated [a] mean annual increase of 2% yr^{-1} between 1951 and 1981 at that site.
>
> Mean concentration concentrations and variability are smaller for CO in the Southern Hemisphere than in the north. The dominant sources of CO in the south may be the oxidation of CH4 and transport from the north. Comparison of recent measurements of CO at Cape Point, South Africa (1978-81) with shipboard data obtained in 1971-1972 indicates that CO in the Southern Hemisphere may have increased by 0.5-1% yr^{-1} (Seiler et al., 1984b). Measurements of CO taken at Tasmania and the South Pole do not yet show statistically significant increases (Fraser et al., 1984).

Unfortunately, the extent to which these measurements can be extrapolated with confidence to estimate global CO change is unclear given the spatial and temporal variability of CO. The importance of establishing a definitive trend

EXHIBIT 2-13

Measured Increases in Tropospheric Concentrations of Methane (CH4)

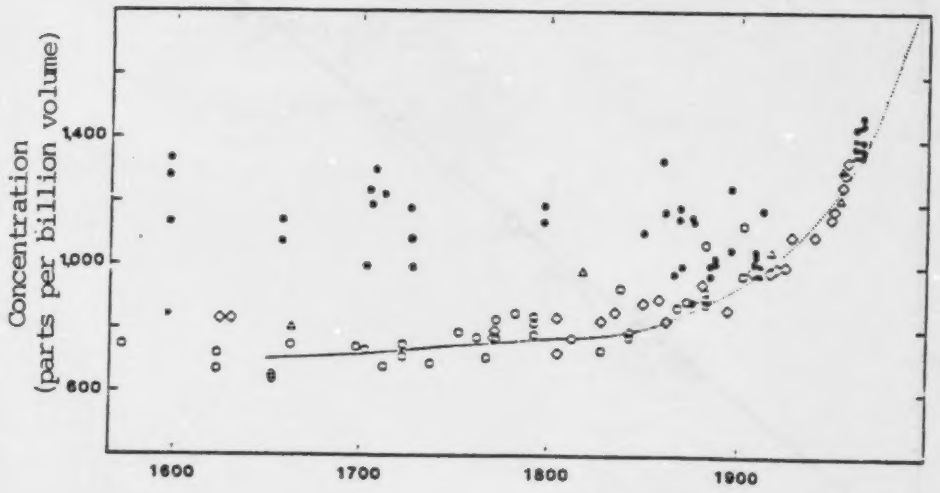


Average concentrations of methane are increasing at approximately 0.017 ppm per year.

Source: Rowland, in NASA, 1986; Figure 5.

EXHIBIT 2-14

Ice Core Measurements of Historical Methane (CH4) Concentrations



Ice core data show that methane concentrations were relatively constant until the time of the Industrial Revolution. Since that time, they have roughly doubled.

Source: Adopted from Pearman et al., 1986.

for CO concentrations is clear, however, since once the CH4 and CO trends are both understood, the fluxes generating them can more easily be derived.

For example, modeling analyses by several investigators (Khalil and Rasmussen 1985a; Levine, Rinsland, and Tennille 1985; Thompson and Cicerone 1986) imply increases in CH4 fluxes from 1850 to 1985 ranging from 15 percent to 70 percent, depending on the magnitude of assumed CO changes during that period. Levine, Rinsland, and Tennille (1985) used their estimates of changes in CO and CH4 concentrations (1 percent and 2 percent, respectively), to estimate a change of 14 percent in methane fluxes and 86 percent in CO fluxes to reconstruct observed atmospheric changes in these gases. The uncertainties in measurements and atmospheric models, however, are still too large to rely upon.

FACTORS THAT INFLUENCE TRACE GAS LIFETIMES

Trace gas molecules, both natural and man-made, are released into the atmosphere at the earth's surface. Unless some rapid process exists for their removal, these molecules are soon distributed throughout the troposphere. The time scale for local vertical mixing is a few weeks; that for east-west mixing about the globe, a few months; and that for exchange between northern and southern hemispheres, a year or two (NAS 1976).

Trace gases can be removed from the troposphere by a number of processes that occur either at the earth's surface or in the atmosphere. Physical processes, such as absorption in the oceans, can remove trace gases from the atmosphere. This is an important process for CO2. Chemical processes, such as reactions with the OH radical, can also remove trace gases from the troposphere. These processes are important for a wide array of gases, particularly methane, HCFC-22, and methyl chloroform. Other trace gases, including CFC-11, CFC-12, CFC-113, Halon-1211, and Halon-1301, are chemically inert. For these gases, transport to the stratosphere is the only significant removal process (NAS 1983).

Transport of trace gases within and between the troposphere and stratosphere involves the vertical motion of large air masses. It is thus independent of the molecular weight or structure of the species involved (NAS 1976). It is a slow process because air exchange is inhibited by the temperature structure of the atmosphere. The stratosphere sits as a permanent air inversion over the troposphere with temperature rising with altitude rather than falling. The troposphere is heated from the surface and is vertically unstable. This inversion inhibits transport.

The average concentration of a trace gas in the troposphere is determined by the balance between the source strength of the trace gas, its rate of chemical transformation in tropospheric destruction, its deposition, and the net flux through the tropopause.

The lifetime of a trace gas in the atmosphere can be defined as the average time its molecules reside there. If at any time, the release of a particular trace gas is suddenly terminated, the residence time, or atmospheric lifetime, is the time required for the concentration to drop to 1/e (37%) of its value at the time of termination (NAS 1976).

LONG-LIVED TRACE GASES

Many stratospheric perturbants are relatively chemically inert in the troposphere. Despite an intense ten year effort to search for alternative sinks for these long-lived gases, their only known significant sink is transport to the stratosphere (NAS 1976; and NAS 1984). Lifetimes for these gases are: 75 (+32/-17) years for CFC-11 and 111 (+289/-46) years for CFC-12 (WMO 1986); 90 years for CFC-113 (NAS 1984); 50 years for CCl4 (WMO 1986); 110 years for Halon-1301 and 25 years for Halon-1211 (NAS 1984); and 150 years for N2O (WMO 1986). Because loss to the stratosphere is slow relative to their current source strength, long lived gases would be expected to accumulate in the troposphere and increase in concentration.

Clearly the rise in concentrations of gases demonstrates this fact. Current concentrations of these trace gases appear far from steady state, and given their current emission levels, concentrations will continue to rise even if emissions do not increase (that is, if emissions do not move further from atmospheric steady state). Thus, if emissions are held constant, tropospheric concentrations will continue to increase -- although ultimately the increase will slow and concentrations will gradually reach equilibrium (steady state). At steady state, the tropospheric concentration will exceed today's concentration.

Neglecting atmospheric feedbacks, a simplified model (See Appendix A, this chapter) of source and loss terms implies that if current CFC-12 emissions are held constant (Exhibit 2-15A), the concentration in the year 2100 would be 1.9 ppbv (Exhibit 2-15B), almost four times higher than the current concentration. To halt a rise in concentrations would require a large shift in emission rates. A reduction of 85 percent in CFC-12 emissions would be required to prevent an increase from current concentrations (Exhibit 2-16A). To hold tropospheric concentrations of CFC-11 constant would require an 80 percent cut in current emissions (Exhibit 2-16B).

Reductions in emissions less than 85 percent would only slow increases in concentrations. Exhibit 2-17 shows the concentrations of CFC-12 associated with different emission trajectories. For example, a 15 percent decrease in current emissions of CFC-12 would imply a tropospheric concentration in 2100 of 1.6 ppb, approximately 3.9 times higher than the current concentration. A 50 percent decrease in current emissions of CFC-12 would still result in increases in tropospheric concentrations, and by 2100 a concentration of 1.01 ppbv, 2.5 times the current concentration.

The disequilibrium for these long-lived gases between current emissions and tropospheric concentrations has implications for the certainty of estimating future concentrations. Future tropospheric concentrations will depend heavily on past emissions. Even total termination of additional emissions of long-lived gases to the atmosphere would not greatly alter concentrations for decades. In addition, with long lived gases, preventing rises in concentration will be difficult because only large reductions will bring emissions and gases back into equilibrium. Freezes or small reductions will allow concentrations to rise for decades.

EXHIBIT 2-15A

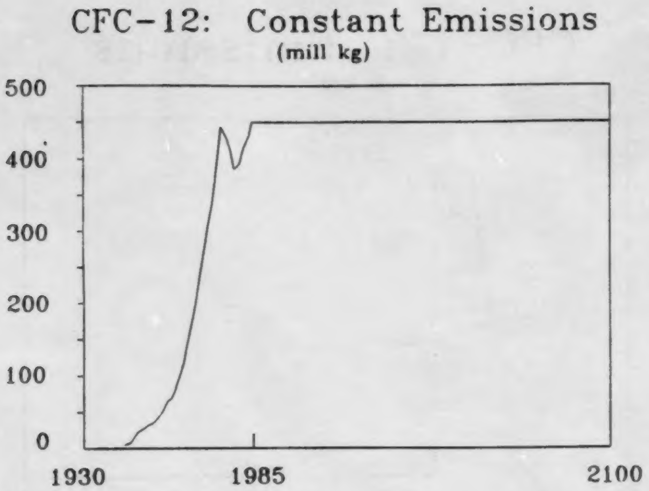
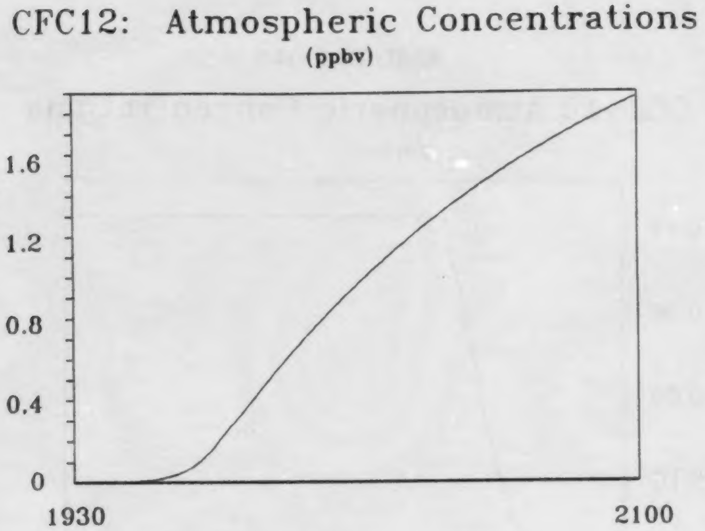


EXHIBIT 2-15B



If future emission of CFC-12 were held constant at today's levels (A), atmospheric concentrations would continue to rise for over 100 years (B). Computed with simplified model of source and loss terms. See Appendix to Chapter 2.

Source: Hoffman, 1986.

EXHIBIT 2-16A

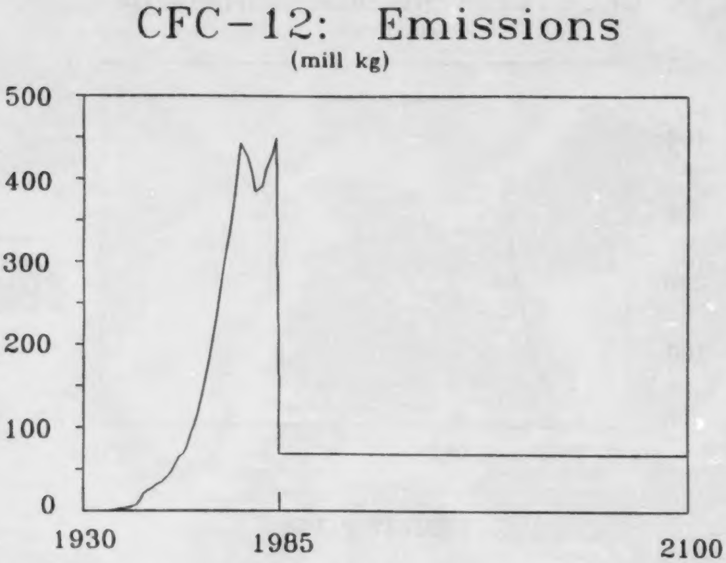
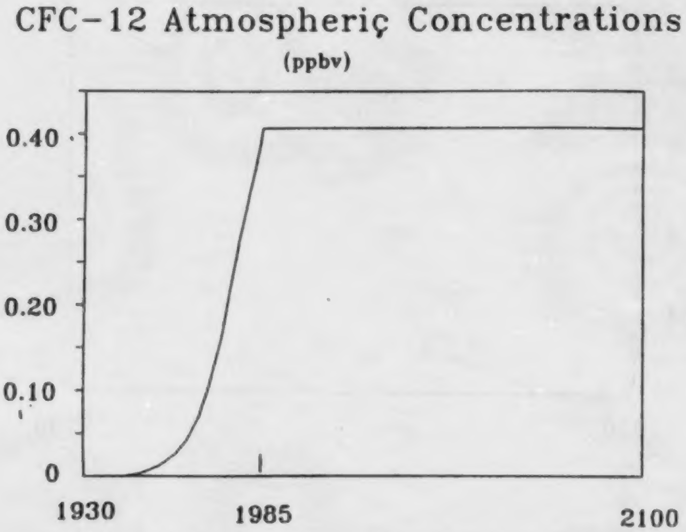


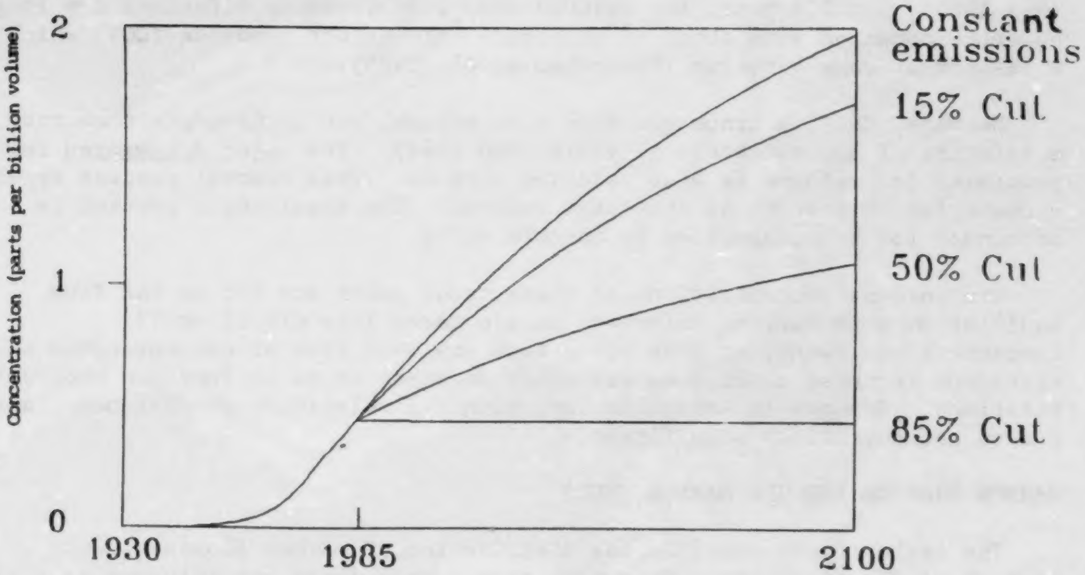
EXHIBIT 2-16B



A reduction of 85% in CFC-12 emissions (A) would be required to hold concentrations constant (B). Computed with simplified model of source and loss terms. See Appendix to Chapter 2.

EXHIBIT 2-17

CFC-12: Atmospheric Concentrations from Different Emission Trajectories



For CFC-12, holding emissions constant at 85% of today's level (a 15 percent cut), would allow concentrations to increase by a factor of four. Only an emission cap at 15 percent of today's level (an 85 percent cut) could hold concentrations constant. Computed with simplified model of source and loss terms. See Appendix to Chapter 2.

Source: Hoffman, 1986.

TRACE GASES WITH SHORTER LIFETIMES

Several other stratospheric perturbants have relatively shorter lifetimes. Their concentrations will depend on emissions from relatively shorter time periods. Among the anthropogenic trace gases, HCFC-22 and methyl chloroform (CH3CCl3) have lifetimes shorter than 50 years.

HCFC-22 and CH3CCl3 are partially halogenated (i.e., they contain C-H bonds) and react with OH, the hydroxyl radical, in the troposphere. This chemical removal process is responsible for their shorter lifetimes: 20 years for HCFC-22 (NAS 1984), and 6.5 years for CH3CCl3 (WMO 1986). These lifetimes are long, however, compared with those of molecules like carbon monoxide (CO), which have a 16-week average lifetime (Ramanthan et al. 1985).

Methane (CH4), a trace gas with both natural and anthropogenic sources, has a lifetime of approximately 11 years (WMO 1986). The major documented removal processes for methane is also reaction with OH. This removal process appears to account for 98 percent of the total removal. The remaining 2 percent is accounted for by consumption by aerobic soils.

The current concentrations of these trace gases are not as far from equilibrium with current emissions as are gases like CFC-11 or 12. Concentrations twenty or more years from now will rise at current rates only if emissions increase or if chemical sinks decrease so as to lengthen chemical lifetimes. Changes in emissions can, within a relatively shorter time, alter future concentrations significantly.

CARBON DIOXIDE AND THE CARBON CYCLE

The carbon cycle controls the distribution of carbon dioxide (CO2) throughout the biosphere. Emissions from fossil fuels are only one part of this complex combination of biogeochemical processes. Other components of the carbon cycle are the uptake of carbon by the terrestrial biosphere and the uptake, absorbtion, and outgassing of CO2 in the oceans. The carbon cycle is discussed in greater detail in Chapter 4 of this assessment. Interested readers may also wish to consult the "state-of-the-art" report Atmospheric Carbon Dioxide and the Global Carbon Cycle, recently issued by the U.S. Department of Energy (Trabalka 1985) and The Carbon Cycle and Atmospheric CO2: Natural Variations Archean to the Present (Sundquist and Broecker 1985).

SOURCE GASES FOR STRATOSPHERIC SULFATE AEROSOL

Stratospheric sulfate aerosols (OCS, CS2) and volcanically injected chlorine can in some cases reach and perturb the stratosphere. While most sulfur gases emitted into the troposphere from natural and anthropogenic sources are too reactive and/or too soluble to reach the stratosphere, carbonyl sulfide (OCS) is an important exception (Crutzen 1976; Sze and Ko 1979). Apart from volcanic injection, the major source of sulfur to the stratosphere is OCS from the troposphere.

OCS, the most abundant gaseous sulfur carrier in the atmosphere, has a nearly uniform concentration in the free troposphere of 500 pptv and an estimated lifetime of more than one year (WMO 1986). Current estimates of the global sources and sinks of OCS have been derived by extrapolating a very limited data base and are subject to large uncertainties. Natural sources include oceans, soils, and coastal salt marshes and an important secondary

Turco et al. (1980) conclude that "the total global source of OCS is 1 to 10 tg per year, and that a large fraction of this, as much as 50%, may result from anthropogenic activities related both to fuel processing and consumption." They note that the size of the OCS combustion source is sensitive to the use of sulfur recovery systems: untreated stack gases have very low OCS concentrations, while the use of sulfur recovery systems generates OCS. Increases in the future use of scrubbers could thus increase OCS emissions.

A small contribution to OCS emissions may result from the use of catalytic convertors in automobiles, which occasionally generate large quantities of (H2S) and OCS. Negligible anthropogenic sources include direct commercial production, cigarette smoke, vapors from cooking grain mashes, and Kraft mills. Future concentrations of OCS cannot now be reliably predicted due to a lack of research in this area. Given the possible importance of aerosols in the stratosphere, this deficiency needs to be remedied (Turco et al. 1980).

Volcanoes have long been recognized as dominant sources of stratospheric sulfate and aerosol. It has also been clear for some time that they could also be sources of stratospheric chlorine. Little research has been done to quantify this source. The amount of volatile material in the pre-eruption magma varies from volcano to volcano, the amount of chlorine in the volatile material varies similarly, and soluble, polar compounds like hydrochloric acid (HCl) can be removed during the rapid rise (and condensation) of a volcanic plume. Hence volcanoes are sporadic sources not easily described by annual averages. It is clear, however, that only a fraction of volcanic eruptions penetrate the stratosphere (WMO 1986).

APPENDIX A

CFC EMISSIONS-CONCENTRATIONS MODEL

A simplified atmospheric parameterization, taken from Rind and Lebedeff (1984), can be used to relate future tropospheric CFC-11 and CFC-12 concentrations to their future surface emissions.[1] Their documentation follows:

> ... we estimate these residence times t_k to be 75 years for F11 and 150 years for F12.[2] Thus, for the year m the concentration $C_k(m)$ as a function of the annual release $R_k(m)$ is given by:
>
> $$C_k(m) = f_k \sum_{e=1940}^{m} e^{-(m-e)/t_k} R_k(e). \qquad \text{(A)}$$
>
> According to our estimate the annual release for both fluorocarbons during the year 1940 was zero. The constant f_k relates the mixing ratios C_k in ppbv of fluorocarbons to their annual release R_k (in millions kg/year). These constants of proportionality were determined by comparing the computed concentrations with observed globally averaged values of F11 and F12 for the years 1977-1979 as reported by NOAA (1979) and (1980) in Geophysical Monitoring for Climatic Change No. 7 and No. 8. Global average concentrations were computed from the results of measurements of concentrations at five stations. Locations of these stations and the measured values are summarized in Tables 4 and 5 [Exhibits A-1 and A-2, this paper]. We assumed the concentrations to be zonally uniform and fitted expressions
>
> $$C_k(\lambda,\phi) = \sum_{e=1}^{5} a_e \sin^{e-1}(\phi)$$
>
> to the data in Exhibit 2-4. Here ϕ denotes latitude and λ longitude. The global averages are shown in the last column of Table 4 (Exhibit A-1, this paper). The constants of proportionality f_k were obtained by fitting expressions (A) to the data, yielding $f_{11} = 4.6395*10^{-5}$ and $f_{12} = 5.3279*10^{-5}$ ppb/millions/kg/year).

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[1] The Rind and Lebedeff method does not consider changes in atmospheric processes that may occur as a result of potential stratospheric ozone depletion. Results from one-dimensional (1-D) model calculations indicate that if stratospheric ozone levels decrease, the increased ultraviolet radiation that penetrates to the troposphere may reduce CFC-11 and CFC-12 lifetimes and hence the growth in their tropospheric concentrations. This process is unlikely to be significant in scenarios of low CFC growth (Stolarski, personal communication).

[2] While the Rand and Lebedeff estimate for the CFC-12 lifetime differs from that of WMO (1986), the estimate is within the uncertainty band given by WMO.

EXHIBIT A-1

Concentrations of Fluorocarbons (ppbv)

	STATION					
YEAR	BRW	NWR	MLO	SMO	SPO	GLOBAL
	Fluorocarbon 11 (CCl3F)					
1977	0.159	0.155	0.148	0.140	0.139	0.145
1978	0.172	0.168	0.162	0.153	0.154	0.159
1979	0.182	0.175	0.174	0.164	0.175	0.171
	Fluorocarbon 12 (CCl2F2)					
1977	0.292	0.275	0.270	0.256	0.248	0.262
1978	0.302	0.296	0.291	0.273	0.271	0.282
1979	0.301	0.301	0.296	0.276	0.306	0.290

EXHIBIT A-2

Locations of the Stations

NAME	ABREV.	LONGITUDE	LATITUDE
Point Barrow	BRW	130.60°W	70.32°N
Niwot Ridge	NWR	105.63°W	40.05°N
Mauna Loa	MLO	155.58°W	19.53°N
American Samoa	SMO	170.56°W	14.25°S
South Pole	SPO	24.80°W	89.98°S

Source: National Oceanic and Atmospheric Administration (1979) Geophysical Monitoring for Climate Change No. 7, Summary Report 1978, B.G. Bendonca, (ed.).

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CHAPTER 3

PROJECTIONS OF EMISSIONS OF INDUSTRIALLY-PRODUCED POTENTIAL OZONE MODIFIERS*

SUMMARY

Human activities are the only source of emissions for three important classes of chemicals that may modify the amount of ozone in the atmosphere: (1) chlorofluorocarbons (CFCs); (2) chlorocarbons; and (3) Halons. CFCs and chlorocarbons release free chlorine into the stratosphere, and Halons release free chlorine and/or bromine into the stratosphere (there are other natural sources of chlorine in the atmosphere).

Historically, CFCs have contributed more to potential ozone modification than have chlorocarbons and Halons. The most widely used CFCs are CFC-11 and CFC-12, which account for 80 percent of today's CFC production worldwide. CFC-113 and HCFC-22 are also commercially produced in large quantities. A variety of specialty CFCs are produced in small quantities.

Due to their unique physical properties, CFCs are employed in a diverse set of applications, including: aerosol propellants; refrigeration; air conditioning; solvents; and foam production. Substitutes for CFCs or the CFC-related product exist for many of these applications. In some applications (such as refrigeration), the CFCs remain captured in the product for many years before being released.

Data describing the historical production and use of CFCs for various parts of the world have been collected by a variety of organizations. The most comprehensive data on the production of CFC-11 and CFC-12 have been compiled by the Chemical Manufacturers Association (CMA) from reports by CFC producers. These data indicate that production of CFC-11 and CFC-12 peaked in 1974, and subsequently declined through 1982. Combined CFC-11 and CFC-12 production since 1982 has increased each year.

The decline in the production of CFC-11 and CFC-12 from 1974 to 1982 is attributable primarily to the reduction in their aerosol propellant use. The United States implemented a ban on the use of CFCs in nonessential aerosol applications in 1978. Several other countries and groups of countries have instituted controls on aerosol applications with varying degrees of stringency.

During the period when aerosol applications were declining, nonaerosol applications (refrigeration, air conditioning, solvents, foam production) continued to increase. In 1978, nonaerosol usage exceeded aerosol usage, and by 1985 nonaerosol usage was in excess of 70 percent of total CFC applications. Therefore, CFC usage is increasingly dominated by nonaerosol applications.

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* Better information about estimates of the use of CFCs in different countries and Halon projections became available in late summer of 1987. The body of this chapter does not incorporate these changes; however, in the Appendix of this Chapter these data are shown. The data shown in the Appendix of this chapter are not used in the Risk Assessment.

Long term projections of CFCs are needed for risk assessment because of their long lifetimes. Projections of the potential future demand for CFCs were presented at a UNEP economics workshop on CFCs in May of 1986, and are found in the trade literature. Indications are that in the absence of additional controls on production, use, or emission, total CFC production is expected to increase in the foreseeable future. Underlying this growth of CFCs is the expectation that aerosol applications will continue to decline and level off. The future growth in production is expected to be driven by increases in nonaerosol applications. However, long term projections of potential growth are viewed as very uncertain. In Chapter 18, we define a series of "what if" scenarios for testing the atmospheric impacts of continued emission of these ozone depleters that span a wider range of possible emission futures than discussed here. In this chapter, the focus is on what various economic analyses show are the most likely emission trends.

The chlorocarbons (carbon tetrachloride and methyl chloroform) are used primarily as solvents and chemical intermediates. In the United States carbon tetrachloride is primarily used to make CFCs and only a small amount of this use is emitted to the atmosphere. In developing countries carbon tetrachloride is believed to be used as a solvent, resulting in considerable emissions. Methyl chloroform is primarily used as a general purpose solvent worldwide. Future demand for methyl chloroform is expected to grow at a rate similar to rates of growth of economic activity. Future demand for carbon tetrachloride is expected to grow at the same rate as the demand for CFCs.

Halons have been used in hand-held and total-flooding fire extinguishers since the 1970s. Their unique properties make Halons valuable for protecting delicate electronic equipment such as computers. Annual production has been estimated as small (approximately 20,000 kilograms) and emissions have been assumed, by some authors, to be very small because the Halons remain in the fire extinguishers for many years. In the absence of industry led attempts to reduce halons or government regulation, halon production and emissions are expected to grow significantly over the next 15 years, although the potential for long-term growth is uncertain.

FINDINGS

1. HUMAN ACTIVITIES ARE THE ONLY SOURCE OF EMISSIONS FOR THREE CLASSES OF POTENTIAL OZONE-DEPLETING CHEMICALS: CHLOROFLUOROCARBONS (CFCs); CHLOROCARBONS (CARBON TETRACHLORIDE AND METHYL CHLOROFORM); AND HALONS (chapter 3)[1].

   1a. Since their development in the 1930s, CFCs have become useful chemicals in a wide range of consumer and industrial goods, including: aerosol spray cans; air conditioning; refrigeration; foam products (e.g., in cushions and insulating foams); solvents (e.g., electronics); and a variety of miscellaneous uses.

   1b. CFC-11 (CCl_3F) and CFC-12 (CCl_2F_2) have dominated the use and emissions of CFCs, accounting for over 80 percent of current CFC production worldwide. Because of increased demand for its use as a solvent, CFC-113 (CCl_2FCClF_2) has become increasingly important as a potential ozone-depleting chemical.

2. WHILE CFCs USED IN AEROSOLS DECLINED FROM 1974 UNTIL 1984, NONAEROSOL USES OF CFCs HAVE GROWN CONTINUOUSLY AND APPEAR CLOSELY COUPLED TO ECONOMIC GROWTH (chapter 3).

   2a. From 1960 to 1974, the combined production of CFC-11 and CFC-12 from both aerosol and nonaerosol applications grew at an average annual rate of approximately 8.7 percent. Total global CFC-11 and -12 production peaked in 1974 at over 700 million kilograms.

   2b. From 1976 to 1984, sales of CFC-11 and CFC-12 for aerosol applications declined from 432 million kilograms to 219 million kilograms, an average annual rate of decline of over 8 percent. During the same period, sales for nonaerosol applications grew from 318 million kilograms to 476 million kilograms, an average annual compounded growth rate of 5 percent. By 1986, total CFC-11 and -12 global production was nearly that in 1974.

3. STUDIES OF FUTURE PRODUCTION OF CFCs-11 AND -12 PROJECT AN AVERAGE ANNUAL GROWTH RATE OF APPROXIMATELY 1.0 TO 4.0 PERCENT OVER THE NEXT 15 TO 65 YEARS (chapter 3).

   3a. A large number of studies of future global demand for CFCs were conducted by experts from six countries under the auspices of the United Nations Environment Programme. These studies used a variety of methods for estimating both near- and long-term periods. In general, these studies assumed that: (1) demand for CFCs was driven by economic factors; (2) no additional regulations on CFC use were imposed; and (3) consumers or producers do not voluntarily shift away from CFCs because of concern about ozone depletion. These studies provide a range of growth rates for developing alternative baseline scenarios of future CFC use and emissions.

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[1] The chapter references refer to the main body of the risk assessment.

3b. In general, these studies projected that CFC aerosol propellant applications would remain constant or decrease further in many regions of the world.

3c. In the U.S. over the past four decades new uses of CFCs have developed first in refrigeration, then in aerosols, then in foam blowing, and then in solvents.

3d. Studies have projected that growth in developed countries for nonaerosol applications is expected to be driven by increased use in foam blowing (primarily for insulation) and as solvents, and by the continued introduction of new uses. The wide range of estimates of future growth reflects the large uncertainties related to population and economic growth, and technological change.

3e. Studies suggest that future CFC use in developing countries will grow faster (i.e., at a higher rate) than future CFC use in the developed world. Nevertheless, the projected rates for the developing countries are lower than the historical rates that have been experienced in wealthier countries. While these studies were done using aggregate relationships of GNP and CFC use, they made different assumptions about how closely the pattern of CFC use in developing nations would replicate the pattern in developed nations, generally assuming lower use rates. However, evidence from one recently completed study (not completed at the time of the UNEP workshop) indicates that in developing countries the penetration of CFC-using goods may be occurring faster than expected on the basis of the historical relationship in developed nations. If that study is correct, growth in developing nations would be larger than projected in the above-mentioned studies, which generally assumed less penetration in developing nations than had occurred in developed nations.

3f. Three long-term studies of CFC demand report annual average rates of growth for CFC-11 and CFC-12 over the next 65 years ranging from 0.2 percent to 4.7 percent, with a median estimate of about 2.5 percent. The "what if" scenarios used for quantitative risk assessment span a wider range of growth, including one scenario with substantial decline.

3g. Limited studies on CFC-113 and CFC-22 project that in the absence of regulation or voluntary shifts away from these chemicals, their growth will increase at a faster rate than CFC-11 and -12 as new markets develop and existing ones expand (e.g., use of CFC-113 as a solvent in metal cleaning).

4. THE CHLOROCARBONS (METHYL CHLOROFORM AND CARBON TETRACHLORIDE) ARE USED PRIMARILY AS SOLVENTS AND CHEMICAL INTERMEDIATES. ANALYSIS SUGGESTS LIMITED FUTURE GROWTH FOR THESE CHEMICALS (chapter 3).

4a. Methyl chloroform is primarily used as a general purpose solvent. Global use in 1980 was estimated at nearly 460 million kilograms. Limited analysis of future demand indicates that it is expected to grow at the rate of growth of economic activity (as measured by GNP). Factors affecting future demand include possible control on it or other solvents due to their health effects. Thus, use of methyl its use could be increased if CFC-113 use is restricted. Because methyl chloroform has a substantially shorter atmospheric lifetime than CFC-113, it has relatively less potential for depleting ozone.

4b. Carbon tetrachloride is primarily used to make CFCs in the U.S. In developing countries it is also sometimes used as a general purpose solvent. In general, future production and emission of carbon tetrachloride is expected to follow the pattern of production of CFCs.

5. HALONS, ON A PER POUND BASIS, POSE A GREATER THREAT (2-1/2 TO 12-1/2 TIMES) TO OZONE DEPLETION THAN DO CFCs.

5a. Halons have been used in hand-held and total-flooding fire extinguishers since the 1970s. Annual production has been limited (approximately 20,000 kilograms) and emissions have been assumed to be only a small fraction of production based on the assumption that the halons remain inside the fire extinguishers. Recent research suggests the proportion of Halons released may be substantially higher. In the U.S., industrial response to concern about depletion from halons is likely to lead to some voluntary steps to curtail emissions.

5b. A single study has projected future demand for Halons. It indicates that near-term demand is growing rapidly and that production may double by the year 2000. In that study, longer-term demand is judged uncertain and may range from an average annual decline of 1 percent from 2000 to 2050 to an annual increase exceeding 5 percent.

5c. The expected rate of Halon emissions is very uncertain. The one study assumed most production would remain within fire extinguisher systems as part of a growing Halon "bank." That study has been the basis for scenarios used in this analysis.

5d. The historic growth in Halon 1211 concentrations (recently measured at over 20% per year) is significantly higher than the rate assumed for future years in the one existing study.

5e. Discussions with Halon users indicate that Halon 1301 emissions may be underestimated in the study used for this risk assessment. A recent survey showed that existing systems are undergoing widespread testing and accidental discharge occurs more frequently than assumed in prior studies.[1]

5f. Additional analysis of Halon emission estimates are necessary to assess more adequately the risks associated with this trace gas.

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[1] Since this risk assessment was completed, Halon users in the U.S. have taken a variety of steps to reduce emissions. This step is not considered in this Risk Assessment.

INTRODUCTION

Man's activities are the primary source of emissions for several important potential modifiers of stratospheric ozone, including:

- Chlorofluorocarbons (CFCs), including: CFC-11; CFC-12; HCFC-22; and CFC-113;
- Chlorocarbons, including: methyl chloroform and carbon tetrachloride; and
- Halons, including: Halon-1211 and Halon-1301.

The atmospheric concentrations of these gases are driven by their emissions, and by the natural physical processes that destroy and transport them (thereby removing them from the atmosphere). This chapter describes the historical use and emissions of each of these three classes of potential ozone-modifying substances as well as estimates of potential future use and emissions. A long term perspective on emissions is essential for assessing the risks because of the long lifetime of most of these chemicals.

CFCs are discussed first. Historically, these compounds have contributed the most to potential modification of stratospheric ozone.[1] Chlorocarbons are next in importance (despite the fact that their production volume is larger than CFCs), and are discussed second. Finally, the information on the relatively small amount of Halon production and use is presented. Despite their relatively small production volume, Halons are considered to be growing in importance due to their strong potential for modifying stratospheric ozone.

CHLOROFLUOROCARBONS

CFCs are a class of man-made chemicals that contain chlorine, fluorine, and carbon. There are four major CFCs that are produced in commercial quantities:[2]

- CFC-11;
- CFC-12;
- HCFC-22; and
- CFC-113.

CFC-11 and CFC-12 account for the largest share of total CFC production, approximately 80 percent in recent years.

CFCs are used in a variety of applications that require chemicals with a fairly unique set of physical properties. The properties of CFCs that make them valuable include:

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[1] The relative importance of the compounds in terms of stratospheric ozone modification depends on a variety of factors relating to the chemical composition of each substance. Camm et al. (1986) report the following relative importance as of 1985: CFCs -- 77.8 percent; chlorocarbons -- 16.7 percent; and Halons -- 5.6 percent.

[2] Other CFCs produced in limited quantities include: CFC-13, CFC-14, CFC-21, CFC-23, CFC-114, CFC-115, CFC-142b, CFC-152a. (See Hoffmann and Klander 1978, p. 8). Other CFCs with potential applications that are not currently available commercially include CFC-123 and CFC-134a.

- CFCs can be used with a variety of materials, including plastics;
- CFCs are safe to use, they are not flammable and they are relatively nontoxic;
- CFCs have a low boiling point; this factor is important in manufacturing foams and for refrigeration applications; and
- CFCs have good thermodynamic properties.

Exhibit 3-1 displays selected properties of three of the major CFCs.

These properties enable CFCs to be used in a variety of important applications. Initially, CFCs displaced ammonia in early refrigeration applications. Ammonia was used in refrigerators that were replacing ice boxes in the early twentieth century. However, ammonia is more toxic and combustible than CFCs, and consequently the switch to CFCs reduced the hazards of owning a refrigerator.

In the 1950s, aerosol propellant uses of CFCs were first introduced. These applications grew into large markets of personal care products such as hair sprays and deodorants. Also during the 1950s, refrigeration and air conditioning applications grew rapidly. By the 1960s, these applications were well established.

Two new important uses for CFCs were introduced in the 1960s. During this decade, CFC-11 was first used to make plastic foams. These foams are used as seat cushions (such as in furniture and cars) and as carpet backings. The foams are also used as insulation in appliances (such as refrigerators) and buildings. The use of CFC-11 in these foam applications has grown so rapidly that this is now the dominant nonaerosol use of CFC-11. The other major use introduced in the 1960s is the application of CFC-12 to automobile air conditioners. In the U.S., the market for automobile air conditioners has grown rapidly and now is an important use of CFC-12.

The most recent market for CFCs is for applications that require a solvent. In particular, the use of CFC-113 as a solvent in the manufacture of electronic components and computer chips has been expanding rapidly. CFCs are preferred as solvents in these applications because they are mild and are not toxic. Its potential as a solvent for metal cleaning may also be large, but was not explicitly analyzed in this chapter.

Exhibit 3-2 provides the following information about the four major CFCs used by industry today; the major applications; the properties that make them useful; the potential for non-CFC substitutes (there may be CFC-related chemical substitutes such as CFC-123 and FC-134a that are not listed); and the consequences of switching to the substitutes. For example, refrigeration

EXHIBIT 3-1

Selected Properties of CFCs

	CFC-11	CFC-12	HCFC-22	CFC-113	CFC-142b	CFC-123	FC-134a
Chemical Formula	CC13F	CC12F2	CHC1F2	CC12FCC12F2	CH3CC1F2	CHC12CF3	CF3CH2F
Molecular Weight	137.4	120.9	86.5	187.4	100.5	152.9	102
Boiling Point, °F	74.8	-21.6	-41.4	117.6	14.4	80.7	-15.7 F
Freezing Point, °F	-168	-252	-256	-31	-204	NA	NA
Vapor Pressure, psig							
At 70°F	13.4*	70.2	122.5	21.2 (at 77°F)	NA	NA	NA
At 130°F	24.3	181.0	300.0	NA	NA	NA	NA
Liquid Density, gm/cm^3							
At 70°F	1.485	1.325	1.209	1.565 (77°F)	1.113 (77°F)	1.475 (at 60°F)	NA
At 130°F	1.403	1.191	1.064	NA	NA	NA	NA
Atmospheric Lifetime, years	84	148	33	88	NA	NA	6.4

* psia.

Sources: Hoffmann, B.L., and D.S. Klander (1978), Final EIS Fluorocarbons: Environmental and Health Implications, FDA, p. 9.

Connell, P.S. (1986), "A Parameterized Numerical Fit to Total Column Ozone Changes Calculated by the LLNL 1-D Model of the Troposphere and Stratosphere," Lawrence Livermore National Laboratory, Livermore, California, p. 4.

WHO Criteria Document on Chlorofluorocarbons (1986), Draft Report, Environmental Criteria and Assessment Office, U.S. EPA, Cincinnati, Ohio, p. 2-10.

Memo from Lynn Erikson, Radian Corporation to Neil Patel, EPA, July 1986.

Anderson, L.G. (1980), "The Atmosphere Chemistry of 1,1,1-2-tetrafluoroethane," General Motors Research Laboratory, Warren, Michigan, GMR-3450.

EXHIBIT 3-2

CFC Characteristics and Substitutes

Application	Type of CFC Used	Key Characteristics of CFC Used	Potential Alternatives	Potential Consequences of Using Alternatives
Refrigeration	CFC-11 CFC-12 CFC-22	Thermodynamic properties Safety Cost	Ammonia Sulphur Dioxide Methyl Chloride	More toxic Combustible Corrosive Explosive Less energy efficient
Air Conditioning	CFC-11 CFC-12 CFC-22 CFC-113	Thermodynamic properties Safety Cost	Ammonia Sulphur Dioxide Methyl Chloride	More toxic Combustible Corrosive Explosive Less energy efficient
Automobile Air Conditioning	CFC-12	Thermodynamic properties Safety Cost	Ammonia Sulphur Dioxide Methyl Chloride	More toxic Combustible Corrosive Explosive Less energy efficient
Plastic Foam insulation	CFC-11	Thermodynamic properties	None for high-efficiency insulation	Less effective
	CFC-12	Safety Cost	Pentane (some foams) Methylene Chloride (some foams)	Combustible Processing difficulties Toxicity
Solvents	CFC-11	Ability to displace all contaminants	Perchloroethylene Trichlorethylene Trichloroethane	More toxic Uses more energy
	CFC-113	Chemically inert Safety		
Aerosol Propellants	CFC-11 CFC-12	Thermodynamic properties Safety	Hydrocarbons Carbon Dioxide	Combustible Reduced product quality

CFCs are used in a diverse set of applications. Substitutes for CFCs have undesirable consequences in many applications.

Source: Alliance for Responsible CFC Policy (1980), "An Economic Portrait of the CFC-Utilizing Industries in the United States," Washington, D.C.

applications use CFCs 11, 12, and 22. These compounds are used because of their thermodynamic properties, safety, and low cost. Potential alternatives to these compounds include ammonia, sulfur dioxide, and methyl chloride. However, these chemicals are more toxic, flammable, corrosive, explosive, and/or less energy efficient than CFCs. Analogous descriptions are shown for the other applications.

Historical Production and Emissions

Data on the production of CFC-11 and CFC-12 have been collected by:

- The Chemical Manufacturers Association (CMA) for the years 1931 to 1985;
- The United States International Trade Commission (ITC); and
- The European Economic Community (EEC).

The CMA data were supplied by 21 CFC-producing companies that operate plants around the world. These companies and the locations of their plants are listed in Exhibit 3-3. These reporting companies represent CFC production in almost all of the world except for India, Argentina, the East Bloc countries, and China. Production is known to take place in Argentina and India, but data on their production is sparse, and the level of production is believed to be low.

The most recent report issued by the CMA is "Production, Sales, and Calculated Release of CFC-11 and CFC-12 Through 1985," September, 1986. Exhibit 3-4 lists the historical production data for CFC-11 and CFC-12 reported to the CMA. Exhibit 3-5 displays these data for CFC-11 and CFC-12 combined in a graphical form for 1960 to 1985. As the exhibits show, total production increased rapidly throughout the 1960s and early 1970s, reaching a maximum of 813 thousand metric tons in 1974. During this period, the combined production of these two CFCs grew at an average rate of 14 percent per year.

However, beginning in the mid-1970s, public attention focused on the potential for CFCs to deplete stratospheric ozone. In response to these concerns, the United States, a major producer of CFCs, instituted a ban on the use of CFCs in nonessential aerosol propellant applications in 1978. Several other countries also imposed controls on the production and use of CFCs with varying degrees of stringency. For example, the members of the European Economic Community (EEC) agreed to reduce the use of CFCs in aerosols to 70 percent of what they had been in 1976. The subsequent use of CFC-11 and CFC-12 in aerosols as reported by the EEC (1985) is displayed in Exhibit 3-6.

The effect of these controls on aerosol applications, as well as the public perception of CFC dangers, is clearly evident; total production reported to CMA began to decline in 1975. This decline was driven by reductions in the use of CFC-11 and CFC-12 in aerosol propellant applications, which occurred in both the U.S. and the EEC.

In contrast to the decline in production for aerosol propellant applications, production of CFCs for nonaerosol applications reported to CMA continued to increase throughout the 1970s and the 1980s (1976-1985) at an

EXHIBIT 3-3

Companies Reporting Data to CMA

The following is a listing of the reporting companies inclusive of any related subsidiaries and/or joint ventures that reported CFC production and release data:

1. Akzo Chemie B.V. (Holland)
2. Allied Corporation (U.S.)
    (a) Allied Canada Inc. (Canada)
    (b) Quimobasicos, S.A. (Mexico)
3. Asahi Glass Co., Ltd. (Japan)
4. ATOCHEM, S.A. (France)
    (a) Pacific Chemical Industries Pty. Ltd. (Australia)
    (b) Ugimica S.A. (Spain)
    (c) Produven (Venezuela)
5. Australian Fluorine Chemical Pty. Ltd. (Australia)
6. Daikin Kogyo Co., Ltd. (Japan)
7. Du Pont Canada, Inc. (Canada)
8. Du Pont Mitsui Fluorochemicals Co., Ltd. (Japan)
9. E.I. du Pont de Nemours & Company, Inc. (U.S.)
    (a) Du Pont de Nemours (Netherlands) N.V.
    (b) Ducilo S.A. (Argentina)
    (c) Du Pont do Brasil S.A. (Brazil)
    (d) Halocarburos S.A. (Mexico)
10. Essex Chemical Corporation (Racon) (U.S.)
11. Hoechst AG (West Germany)
    (a) Hoechst Iberica (Spain)
    (b) Hoechst do Brasil Quimica e Farmaceutics S.A.
12. Imperial Chemical Industries PLC (England)

    African Explosives & Chemical Industries, Ltd.

EXHIBIT 3-3 (Continued)

Companies Reporting Data to CMA

13. I.S.C. Chemicals Ltd. (England)
14. Kaiser Aluminum & Chemical Corporation (U.S.)
15. Kali-Chemie Aktiengesellschaft (West Germany)
16. Kali-Chemie Iberia SA (Spain)
17. Montefluos S.p.A. (formerly Montedison S.p.A.) (Italy)
18. Navin Fluorine Industries (India)
19. Pennwalt Corporation (U.S.)
20. Showa Denko, K.K. (Japan)
21. Societe des Industries Chimiques du Nord de la Grece, S.A. (Greece)
22. Union Carbide Corporation (U.S.)

    (Union Carbide ceased production in 1977. CFCs resold by Union Carbide are included).

Source: CMA (1986), "Production, Sales, and Calculated Release of CFC-11 and CFC-12 Through 1985," Schedule 1, Listing of Reporting Companies, Washington, D.C.

EXHIBIT 3-4

Production of CFC-11 and CFC-12 Reported to CMA
(millions of kilograms)

Years	CFC-11	CFC-12
1931	-	0.5
1932	-	0.1
1933	-	0.3
1934	-	0.7
1935	-	1.0
1936	0.1	1.7
1937	0.1	3.1
1938	0.1	2.8
1939	0.1	3.9
1940	0.2	4.5
1941	0.3	6.3
1942	0.3	5.9
1943	0.4	8.2
1944	0.4	16.7
1945	0.4	20.1
1946	0.7	16.6
1947	1.3	20.1
1948	3.0	24.8
1949	4.5	26.1
1950	6.6	34.6
1951	9.1	36.2
1952	13.6	37.2
1953	17.3	46.5
1954	20.9	49.1
1955	26.3	57.6
1956	32.5	68.7
1957	33.9	74.2
1958	29.5	73.4
1959	35.6	87.6
1960	49.7	99.4
1961	60.5	108.5
1962	78.1	128.1
1963	93.3	146.4
1964	111.1	170.1
1965	122.8	190.1
1966	141.0	216.2
1967	159.8	242.8
1968	183.1	267.5
1969	217.3	297.3
1970	238.1	321.1

EXHIBIT 3-4 (Continued)

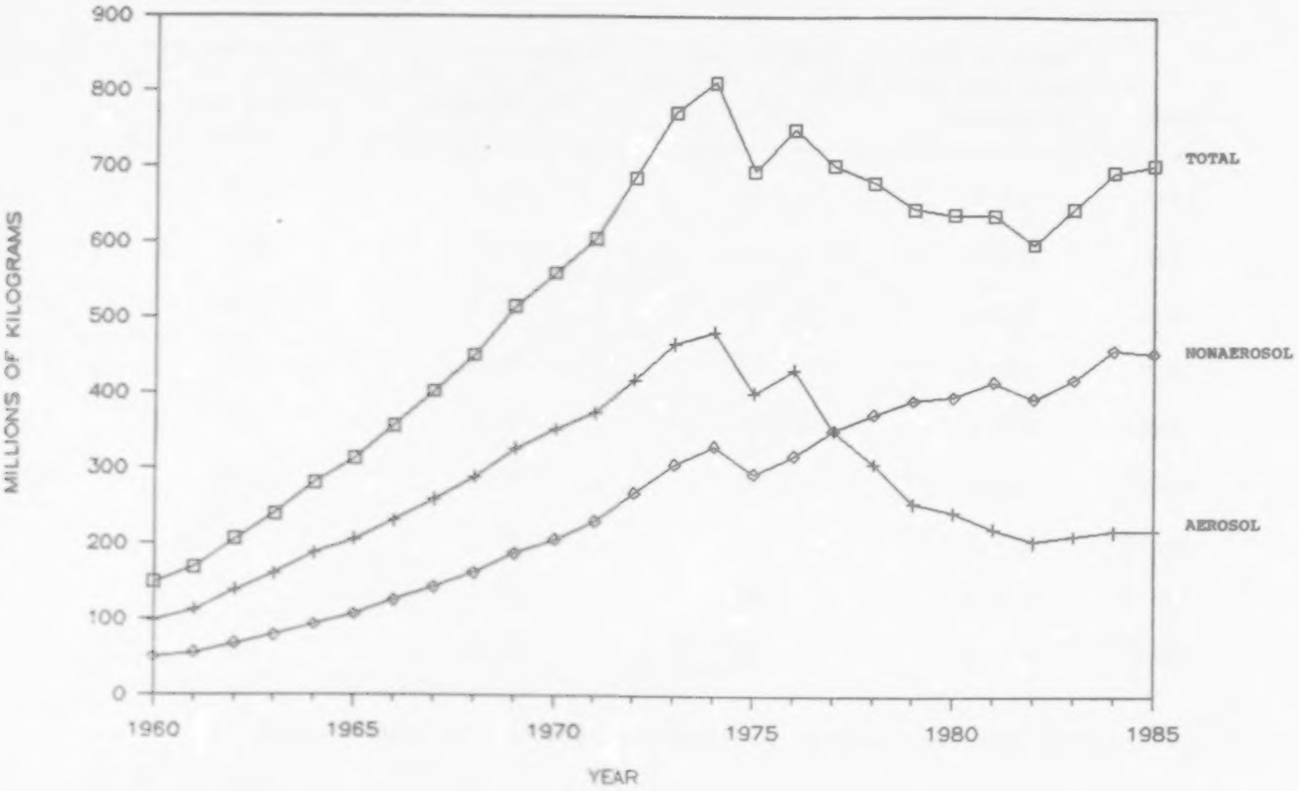
Production of CFC-11 and CFC-12 Reported to CMA
(millions of kilograms)

Years	CFC-11	CFC-12
1971	263.2	341.6
1972	306.9	379.9
1973	349.1	423.3
1974	369.7	442.8
1975	314.1	381.0
1976	339.8	410.7
1977	320.5	382.8
1978	308.9	372.1
1979	289.5	357.2
1980	289.6	350.2
1981	286.9	351.3
1982	271.4	328.0
1983	291.7	355.3
1984	312.4	382.1
1985	326.8	376.3

Source: CMA (1986), "Production, Sales, and Calculated Release of CFC-11 and CFC-12 Through 1985," Schedules 2 and 3, Washington, D.C.

EXHIBIT 3-5

Historical Production of CFC-11 and CFC-12



Total reported production of CFC-11 and CFC-12 increased rapidly throughout the 1960s and 1970s, reaching a maximum of 813 thousand metric tons in 1974. Aerosol applications declined since the mid-1970s, while nonaerosol applications continued to increase. (Note: aerosol/nonaerosol divisions prior to 1976 are estimates.)

Source: CMA (1986), "Production, Sales, and Calculated Release of CFC-11 and CFC-12 Through 1985,." Washington, D.C.

EXHIBIT 3-6

CFC-11 and CFC-12 Used in Aerosol and Nonaerosol Applications in the EEC

Year	Aerosol Use (millions of kilograms)	Aerosol Use Relative to 1976 (percent)	Nonaerosol Use (millions of kilograms)	Nonaerosol Use Relative to 1976 (percent)
1976	176.9	100	67.1	100
1977	162.5	92	70.4	105
1978	150.4	85	81.0	121
1979	136.5	77	83.0	124
1980	126.4	71	90.4	135
1981[a/]	116.1	66	93.6	139
1982[a/]	111.7	63	95.1	142
1983[a/]	113.9	64	102.5	153
1984[a/]	114.7	65	103.1	154

[a/] Includes data for Greece, whereas the 1976 to 1980 data do not.

Source: EEC (1985), "Chlorofluorocarbons in the Environment: Updating the Situation," Communication from the Commission to the Council.

average rate of over five percent per year. Reported use of CFCs for nonaerosol applications in the EEC has also increased during this period (see Exhibit 3-6).

The CMA reports that the largest nonaerosol use of CFC-11 is currently as a blowing agent for making closed cell foam (CMA 1986, Schedule 5). In this application, the CFCs not only help form the cells in the foam, but they also increase the insulating properties of the foam. The CMA estimates that the use of CFC-11 for this application currently accounts for approximately 36 percent of total CFC-11 production, and that it more than doubled from 1976 to 1985, growing at an annual average rate of over 9 percent. The second largest nonaerosol application is reported by CMA to be as an auxiliary blowing agent in the production of open cell foams, accounting for approximately 19 percent of current CFC-11 production. Refrigeration is reported as accounting for 8.2 percent, and all other uses account for 5.7 percent.

Hammitt (1986) developed independent estimates of the shares of CFC-11 production going to each of the applications identified by the CMA. These estimates were developed by estimating the intensity of use of CFCs in each of its applications and then estimating the amount of production of each application (e.g., foams, refrigerators, aerosol products, and miscellaneous). Hammitt's results are very similar to the CMA estimates, and are compared in Exhibit 3-7.

As shown in the exhibit, Hammitt's estimates conform closely with the CMA numbers. However, Hammitt's method reportedly resulted in estimates of CFC-11 use that are eight percent less that the reported total production. This discrepancy is listed by Hammitt under "unallocated" in Exhibit 3-7, and it indicates that while there is general agreement on the approximate magnitudes of the use of CFC-11 in its various applications, there is some difficulty in accounting for the total production.

Similar work has been done to estimate the current use of CFC-12. The CMA reports the largest current use to be in refrigeration applications, accounting for 49 percent of the total production in 1985. Between 1976 and 1985 the use of CFC-12 in refrigeration applications (reported to CMA) grew at an average rate of 4.2 percent per year. Aerosol propellant applications are reported as accounting for 32 percent, and the remaining nonaerosol uses are reported as accounting for approximately 19 percent.

Hammitt's estimates for the share of CFC-12 going to various applications are compared to the CMA estimates in Exhibit 3-8. Compared to CFC-11, there is less agreement on the amount of CFC-12 currently being used in its various applications. The primary difference between the CMA and Hammitt estimates is that Hammitt has only 27 percent of the production going to refrigeration applications, while CMA has 49 percent. This difference appears to be accounted for by a 22 percent share listed as "unallocated" by Hammitt.

The differences in the Hammitt and CMA allocation estimates indicate that there is some uncertainty regarding the current use of CFC-12.

Describing the allocation of CFC production across its possible applications is required for assessing the current (and future) emissions of the compounds to the atmosphere. Some applications emit their CFCs immediately upon use, and are

EXHIBIT 3-7

Comparison of Estimated CFC-11 Use: 1985

Application	Hammitt Use (10^3 kilograms)	Hammitt (percent of total)	CMA Use (10^3 kilograms)	CMA (percent of total)
Aerosol Propellant	93,700	31	100,500	31
Foam Production:				
Closed Cell	115,800	39	117,300	36
Open Cell	57,000	19	63,500	19
Refrigeration and Air Conditioning	9,900	3	26,900	8
All Other Uses	N/A	0	18,600	6
Unallocated Use	23,600	8	N/A	0
Total	300,000	100	326,800	100

N/A = not applicable.

Sources: Hammitt, J.K., et al. (1986), Product Uses and Market Trends for Potential Ozone-Depleting Substances, 1985-2000, The RAND Corporation, p. 5 and p. 94. CMA (1986), "Production, Sales, and Calculated Release of CFC-11 and CFC-12 Through 1985," Schedule 5.

EXHIBIT 3-8

Comparison of Estimated CFC-12 Use: 1985

Application	Hammitt		CMA	
	Use (10^3 kilograms)	(percent of total)	Use (10^3 kilograms)	(percent of total)
Aerosol Propellant	115,600	32	119,700	32
Foam Production:				
Closed Cell	42,800	12	30,200	8
Open Cell	-		20,400	5
Refrigeration and Air Conditioning	98,300	27	185,000	49
All Other Uses	25,400	7	21,000	6
Unallocated Use	82,900	22	N/A	0
Total	365,000	100	376,300	100

N/A = not applicable.

Sources: Hammitt, J.K., et al. (1986), Product Uses and Market Trends for Potential Ozone-Depleting Substances, 1985-2000, The RAND Corporation, p. 6 and p. 95. CMA (1986), "Production, Sales, and Calculated Release of CFC-11 and CFC-12 Through 1985," Schedule 6.

termed "prompt emitters." These applications include aerosol propellant, production of open cell (or flexible) foam, solvent applications, and some miscellaneous applications. Other applications store their CFCs for periods of time, often years. These applications include refrigeration, air conditioning, and the production of closed cell rigid insulating foams.

Estimates have been made of the duration for which CFCs are stored in these products (see, for example, Quinn et al. 1986, Gamlen et al. 1986, McCarthy et al. 1977, and Khalil and Rasmussen 1986). Exhibit 3-9 displays the estimates of emissions for 1971 to 1985 developed by the CMA for CFC-11 and CFC-12 based on their assessments of the allocation of production across the end uses and the duration for which CFCs are stored in the various products. As shown in the exhibit, because CFCs are stored in many products, emissions generally do not equal production in any given year.

Data describing CFC production in the East Bloc countries and China are sparse. Very little has been published about the historical and current rates of production in these countries. Published estimates of production in the U.S.S.R. are displayed in Exhibit 3-10 (these values are not included in the CMA total production values shown in Exhibit 3-4). Data have not been reported that divide these production figures into aerosol and nonaerosol applications.

Zhijia (1986) presented estimates of current CFC production in China at the May 1986 UNEP Workshop on the Control of Chlorofluorocarbons. Zhijia reports annual production of "18 thousand tons" for CFCs 11, 12, 13, 14, 21, 22, 112, 113, and 114. Half of this production "is used for high-molecular polymer as raw materials; another half for the production of refrigerant, aerosol propellant etc." (Zhijia 1986, p. 1).

Based on the data reported in Exhibit 3-10 and assumed rates of growth since 1975, Hammitt estimated the 1985 production of CFC-11 and CFC-12 in the "communist" countries to be 41.5 thousand metric tons and 78.7 thousand metric tons, respectively. Using Hammitt's assumption that 15 percent of total CFC-11 and CFC-12 production in these countries is outside the U.S.S.R., the implied annual production for CFC-11 and CFC-12 in the U.S.S.R. is 105 thousand metric tons, for an annual average growth rate from 1975 to 1985 of 10.3 percent. This rate of growth is much lower than the average of 19.6 percent per year from 1968 and 1975. However, the growth rate for production relative to the growth rate of GNP is similar for the two periods. From 1968 to 1975 real GNP in the USSR grew at annual rate of approximately 4.3 percent (CIA 1983). The ratio of the CFC rate of growth to the GNP rate of growth was approximately 4.6 during this period. From 1975 to 1983 real GNP grew at about 2.5 percent per year (CIA 1983), for a ratio of about 4.1. Nevertheless, a recent oral report by Soviet attendees at a UNEP meeting indicates that the current production capacity in the U.S.S.R. may be 60,000 metric tons for CFC-11 and CFC-12.

Production data for the U.S. have been collected by the International Trade Commission (ITC) in its annual series Synthetic Organic Chemicals. In the early 1960s, production in the United States accounted for over 70 percent of total CFC-11 and CFC-12 production reported to the CMA. The U.S. share of production dropped in the 1960s, and since 1975 it has dropped both as a share of total production and in absolute terms. By 1984, the U.S. share of reported production had dropped to 34 percent. Most of the absolute decline in

EXHIBIT 3-9

Estimates of Production and Emissions of CFC-11 and CFC-12 for Reporting Companies

(millions of kilograms)

	CFC-11		CFC-12	
Year	Annual Production	Annual Emissions	Annual Production	Annual Emissions
1971	263.2	226.9	341.6	321.8
1972	306.9	255.8	379.9	349.9
1973	349.1	292.4	423.3	387.3
1974	369.7	321.4	442.8	418.6
1975	314.1	310.9	381.0	404.1
1976	339.8	316.7	410.7	390.4
1977	320.5	303.9	382.8	371.2
1978	308.9	283.6	372.1	341.3
1979	289.5	263.7	357.2	337.5
1980	289.6	250.8	350.2	332.5
1981	286.9	248.2	351.3	340.7
1982	271.4	239.5	328.0	337.4
1983	291.8	252.8	355.3	343.3
1984	312.4	271.1	382.1	359.4
1985	326.8	280.8	376.3	368.4

Source: CMA (1986), "Production, Sales, and Calculated Release of CFC-11 and CFC-12 Through 1985," Table 3.

EXHIBIT 3-10

Published Estimates of U.S.S.R. Production of CFC-11 and CFC-12

(millions of kilograms)

Year	Production
1968	11.2
1969	14.4
1970	16.0
1971	19.1
1972	22.2
1973	24.2
1974	32.1
1975	39.2

Source: Borisenkou, U.P., and Kazakou, Y.E., 1980, "Effect of Freons and Halocarbons on the Ozone Layer of the Atmosphere and Climate," *Tr. Gl. Geofiz Obs. 1980* 438, pp. 62-74, as reported in CMA (1986).

production in the U.S. can be attributed to the 1978 U.S. ban on nonessential aerosol propellant uses of CFCs. Data on U.S. production of CFC-11 and CFC-12 are displayed in Exhibit 3-11. Because of the ban on nonessential aerosol propellant applications of CFC-11 and CFC-12 in the U.S., nearly all of the current production of these CFCs in the U.S. is used for nonaerosol applications.

The EEC publishes data on the production and sales of selected CFCs by EEC producers. Exhibit 3-12 displays these EEC data. As shown in the exhibit, total EEC production of CFC-11 and CFC-12 has remained below the reported 1976 value. Also of note is that a large fraction (approximately one-third) of all CFC-11 and CFC-12 production in the EEC is exported. Unlike the decline in CFC-11 and CFC-12 production since 1976, the data in Exhibit 3-12 indicate a strong increase in the production of CFC-113 and CFC-114 in the EEC.

Less information is available on the historical production and use of other CFCs. Relative to CFC-11 and CFC-12, the quantities produced are small. CFC-113 is an important solvent used in the manufacture of electronic components. Hammitt (1986) estimated the current world production of this CFC at approximately 158 thousand metric tons (due to the lack of data, this estimate is recognized as somewhat uncertain, however). Of note is that the production of this CFC is believed to be growing rapidly, in part in support of the recent growth of the computer industry.

HCFC-22[3] is used in air conditioning applications (particularly in home air conditioners) and in the production of fluoropolymers. When HCFC-22 is used to make fluoropolymers, it is destroyed, and is consequently not emitted to the atmosphere. Gibbs (1986a) reports the production of HCFC-22 in the U.S. to be approximately 110 thousand metric tons in 1983, and that approximately 25 to 35 percent of the production is used in fluoropolymer production. Gibbs also reports production in the OECD countries in 1975 at approximately 75 thousand metric tons. This is the most recent estimate for the OECD countries reported. No estimate is available for the entire world at this time.

Of note is that the trade literature recently reported that a major CFC producer has plans to double the CFC-113 capacity and add 75 percent to its HCFC-22 capacity in Japan.[4] These increases in capacity may indicate expectations of continuing demand for these CFCs.

Other specialty CFCs are produced in small quantities (e.g., CFC-114, CFC-115). Comprehensive information on these CFCs is not available at this time.

Projections of Future Demand for CFCs

A series of studies has examined the potential future demand for CFCs in various parts of the world, 11 studies were submitted to the UNEP Workshop on the control of chlorofluorocarbons (Rome, Italy, May 1986). Most of these 11

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[3] Of note is that HCFC-22 has a much lower ozone-depleting potential than CFC-11, CFC-12, and CFC-113.

[4] Chemical Marketing Reporter, March 10, 1986, p. 3.

EXHIBIT 3-11

Historical Production of CFC-11 and CFC-12 in the U.S.
(millions of kilograms)

Year	CFC-11	CFC-12
1960	32.8	75.5
1961	41.3	78.7
1962	56.6	94.3
1963	63.6	98.6
1964	67.4	103.4
1965	77.3	123.1
1966	77.3	129.9
1967	82.7	140.5
1968	92.7	147.7
1969	108.2	166.8
1970	110.9	170.3
1971	117.0	176.7
1972	135.9	199.2
1973	151.4	221.7
1974	154.7	221.1
1975	122.3	178.3
1976	116.2	178.3
1977	96.4	162.5
1978	87.9	148.4
1979	75.8	133.3
1980	71.7	133.8
1981	73.8	147.6
1982	63.7	117.0
1983	73.1	135.4
1984	84.0	154.1
1985	73.8 p	127.9 p

p = preliminary estimate.

Source: ITC (1986), Synthetic Organic Chemicals.

EXHIBIT 3-12

EEC Production and Sales Data
(millions of kilograms)

Year	CFC-11 and CFC-12			CFC-113 and CFC-114		
	Production a/	EEC Sales	Exports	Production	EEC Sales	Exports
1976	326.4	244.0	83.6	23.5	17.6	5.2
1977	319.1	233.0	81.2	23.9	19.3	5.7
1978	307.0	231.4	82.2	N/A	N/A	N/A
1979	304.2	219.6	81.6	N/A	N/A	N/A
1980	295.7	216.8	79.4	N/A	N/A	N/A
1981 b/	300.1	209.7	88.2	N/A	N/A	N/A
1982	289.0	206.8	82.0	N/A	N/A	N/A
1983	310.2	216.4	91.2	N/A	N/A	N/A
1984	322.2	217.7	103.4	53.6	38.6	12.9

a/ Includes imports. Production may not equal EEC sales plus exports.

b/ Data for 1981 to 1984 include Greece; previous years do not.

N/A = Not available.

Source: EEC (1985), "Chlorofluorocarbons in the Environment: Updating the Situation," Communication from the Commission to the Council, Annex I.

studies analyzed CFC-11 and CFC-12 demand over the next 10 to 15 years. Only three studies examined the potential demand beyond 2000. The general conclusions from the studies can be summarized as follows:

- Future global production and emission of CFCs are expected to increase over the next 15 to 65 years.
- Aerosol propellant applications are expected to remain constant or decrease in many portions of the world.
- Growth in nonaerosol applications is expected to be driven by uses for making foams and electronic equipment.
- Key uncertainties include technological changes over the long term and the patterns of use in developing countries.

This section first describes the methods that were used to project demand, and then summarized the key findings of the studies.

Methods Used for Projecting Future Demand

Two complementary methods have been used to project the future demand for CFCs: (1) a "bottom up" approach; and (2) a "top down" approach. Although the specifics of each author's method vary, the two approaches can be characterized as follows:

- Bottom Up. The bottom up approach relies on a detailed specification of all the products that use CFCs or are made with CFCs (such as aerosols, foams, electronic equipment, and refrigerators). Each of the products is examined to identify its expected future demand and the potential for changes in the intensity with which CFCs are used in the products (i.e., changes in the amount of CFCs required to produce the given product, such as foam). The potential future demand for each of the products is driven by a variety of factors (such as population growth, economic growth, government regulation, and technological change). The intensity of use of CFCs in the identified products may change (i.e., increase or decrease) due to technological change or changes in the relative prices of substitutes. The projection of future CFC demand is compiled by adding the estimates of demand for CFCs in each product. Exhibit 3-13 shows graphically the bottom up approach.

- Top Down. The top down approach does not rely on detailed specifications of the products that use CFCs. Instead, an aggregate relationship between CFC use and general descriptors of overall demand for goods and services is used. These relationships vary, but are

EXHIBIT 3-12

EEC Production and Sales Data
(millions of kilograms)

	CFC-11 and CFC-12			CFC-113 and CFC-114		
Year	Production a/	EEC Sales	Exports	Production	EEC Sales	Exports
1976	326.4	244.0	83.6	23.5	17.6	5.2
1977	319.1	233.0	81.2	23.9	19.3	5.7
1978	307.0	231.4	82.2	N/A	N/A	N/A
1979	304.2	219.6	81.6	N/A	N/A	N/A
1980	295.7	216.8	79.4	N/A	N/A	N/A
1981 b/	300.1	209.7	88.2	N/A	N/A	N/A
1982	289.0	206.8	82.0	N/A	N/A	N/A
1983	310.2	216.4	91.2	N/A	N/A	N/A
1984	322.2	217.7	103.4	53.6	38.6	12.9

a/ Includes imports. Production may not equal EEC sales plus exports.

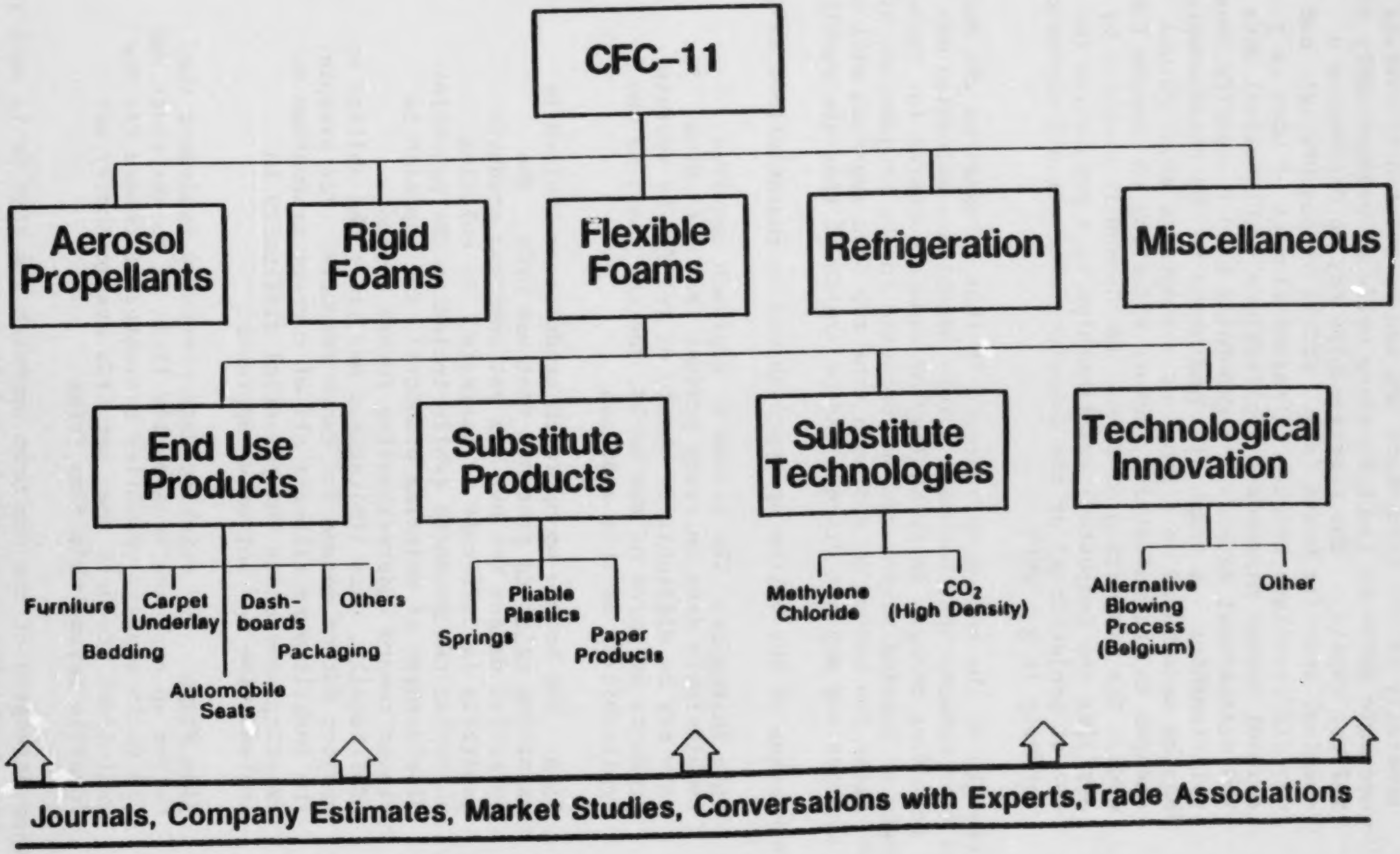
b/ Data for 1981 to 1984 include Greece; previous years do not.

N/A = Not available.

Source: EEC (1985), "Chlorofluorocarbons in the Environment: Updating the Situation," Communication from the Commission to the Council, Annex I.

EXHIBIT 3-13

The Bottom Up Approach


CFC-11
Aerosol Propellants
Rigid Foams
Flexible Foams
Refrigeration
Miscellaneous
End Use Products
Substitute Products
Substitute Technologies
Technological Innovation
Furniture
Bedding
Carpet Underlay
Automobile Seats
Dash-boards
Packaging
Others
Springs
Pliable Plastics
Paper Products
Methylene Chloride
CO2 (High Density)
Alternative Blowing Process (Belgium)
Other
Journals, Company Estimates, Market Studies, Conversations with Experts, Trade Associations

Source: "Overview Paper for Topic #2: Projections of Future Demand," UNEP Workshop, May 1986.

generally of the form where CFC use is related to overall economic activity (such as gross national product (GNP) or GNP per capita). The relationships may be defined on a chemical-specific basis (e.g., CFC-11 versus CFC-12), and may differentiate between different classes of uses (e.g., aerosol versus nonaerosol applications). Historical data and statistical methods are generally used to specify these relationships. A range of adjustments to the relationships may be made based on a range of assumptions about future changes in the underlying factors affecting the demand for CFCs. The projection of future CFC demand is compiled by applying the (adjusted) relationships to a projection (or set of projections) of the descriptors of overall economic activity (e.g., GNP).

The strength of the bottom up approach is that it examines the details of the demand for products that use CFCs. This detailed examination may reveal recent or impending changes in technology or demand patterns for these products. These changes or ongoing trends can be reflected in the projections of CFC demand made using the bottom up approach (the top down approach will not reflect impending changes and may not discern recent trends if they are small).

The weaknesses of the bottom up approach can be characterized as follows:

- Data Intensity. The bottom up approach requires considerable data on every product that uses CFCs. The data may be difficult to obtain or verify for certain products or parts of the world, thereby limiting the applicability of this approach.

- Bias. The bottom up approach tends to be limited to examining existing products that use CFCs. The potential demand for new (as yet unknown) products generally is difficult to estimate. By omitting potential new products (while including the potential displacement of existing products), the approach is biased toward underestimating future demand. Additionally, data limitations may limit the ability to project future demand for known products. For example, the inability to allocate all of current production to existing uses shows the potential difficulty in implementing the bottom up approach.

- Time Frame. The detailed data needed to implement the bottom up approach necessarily limit it to the short run (10 to 15 years). Detailed estimates of demand for the individual products that use CFCs are generally not feasible beyond this time frame.

The major strengths of the top down approach are that it is much less data intensive than the bottom up approach, and it can be used to produce projections of demand beyond the short term. The ability to produce long-term projections is particularly important for the analysis of stratospheric protection because potential ozone-modifying substances (such as CFCs) remain in the stratosphere for very long times (up to 100 years or longer). Consequently, choices regarding what level of stratospheric protection to adopt necessarily require trade offs between short-term and long-term uses of substances like CFCs. Therefore, long-term projections are required.

The top down approach reflects the potential for product innovation and displacement, albeit in an implicit manner. The historical data upon which the method is based include new product introduction, product maturation, and product displacement. For example, during the 1960s and 1970s the use of CFCs for producing foams grew rapidly (product introduction). During the 1970s, the use of CFCs in certain refrigeration applications matured and leveled off in the developed countries. Aerosol propellant applications of CFCs have matured or declined since the mid-1970s. The top down approach implicitly assumes that these types of product introduction, maturation, and displacement (or some adjusted representation of these) will continue into the future.

The top down approach also allows the uncertainty in the long-term role of CFCs to be reflected. Using short-term detailed analyses as a guide, the long-term projections based on the top down approach may be adjusted to reflect alternative assumptions regarding how the key factors affecting future demand may unfold (such as technological change, changes in relative prices, changes in consumer tastes, and changes in regulations). Because these factors are very uncertain over the long term, and may be very different from current conditions, long-term projections based on the top down approach must use a range of assumptions to identify the possible paths of future CFCs use that may be expected.

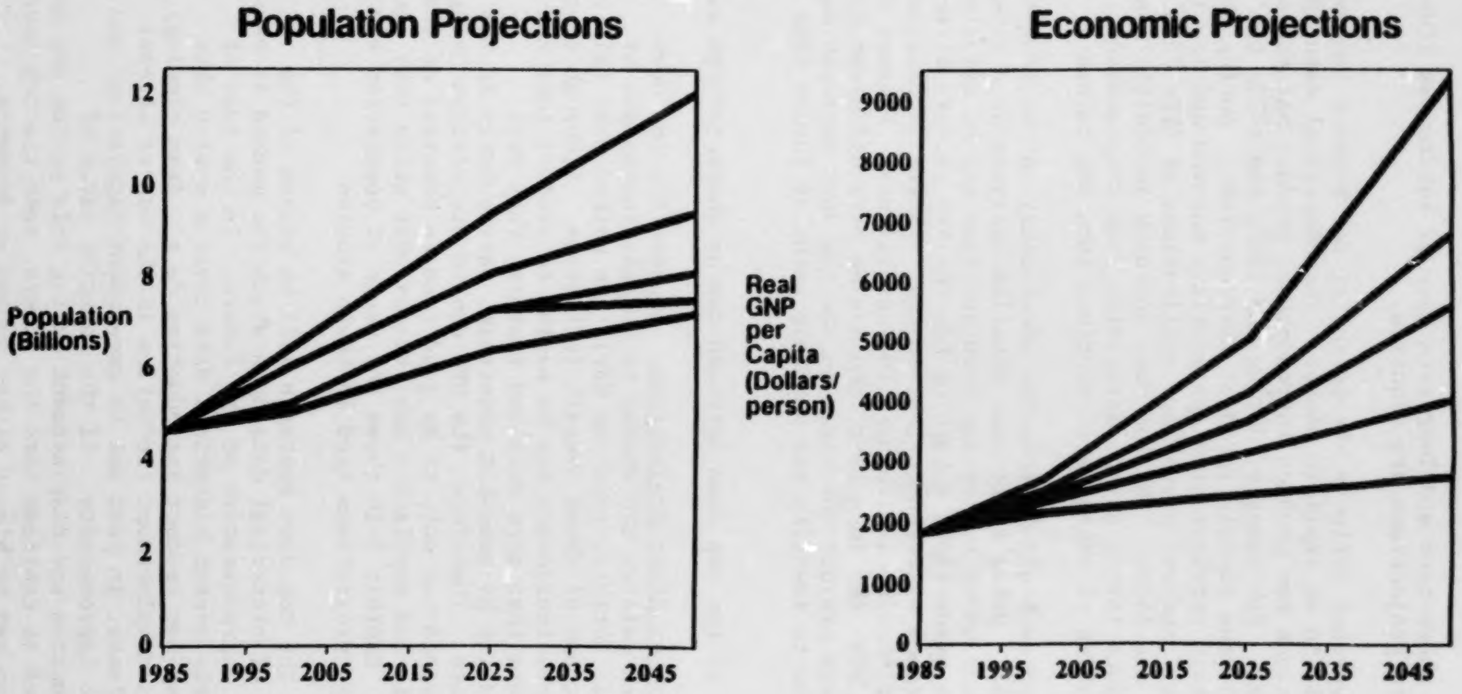
The weaknesses of the top down approach can be characterized as follows:

- Reliance on Other Projections. Because the top down approach relates CFC demand to overall indicators of economic activity (such as GNP), the method must rely on projections of these overall indicators. Although these aggregate indicators may be easier to project into the long term than more detailed factors, they will necessarily be somewhat uncertain, particularly in the out years. Therefore, the CFC demand projections using this method can only be as good (and as precise) as the economic and population projections upon which they are based. Exhibit 3-14 shows the range of population and economic projections used in these studies.

- Bias. The top down approach will be biased if the period of historical data upon which the method is based is not representative of the future. In the case of CFCs, the recent historical data cover a period that includes new product introduction (e.g., foam blowing), product displacement (reduction in the use of aerosol propellants, in part due to government regulation) and product improvements. If the relative rates of introduction and displacement during this period are not expected to continue into the future, then the top down approach may be biased either upward or downward.

EXHIBIT 3-14

Range of Population and GNP Per Capita Projections


Population Projections

Economic Projections

Source: "Overview Paper for Topic #2: Projections of Future Demand," UNEP Workshop, May 1986.

The strengths and weaknesses of the two methods make them natural complements. The bottom up approach provides valuable information about current and ongoing trends, which allows short-term projections to be made. Although these projections may be biased downward, they are useful for calibrating the long-term projections based on the more aggregate top down approach. Together the two approaches provide a rich set of information that indicates the likely range of future CFC demand.

Of note is that both methods are subject to uncertainty. With three exceptions, the papers reviewed did not explicitly quantify the range of uncertainty surrounding their projections. Nevertheless, the uncertainty exists, in part due to uncertainty regarding future economic and population growth (even in the short term), and uncertainty in the future role that CFCs will play in existing and potential new products.

Summary of CFC Projections

Exhibit 3-15 summarizes the methods used in the 11 papers reviewed that contain projections of future demand of CFCs. As shown, six authors used the bottom up approach, four used the top down approach, and one author used a mixed approach. Also shown in the exhibit are the CFCs covered by each author, the portion(s) of the world covered, and the time period analyzed (short term or long term).

Exhibit 3-16 summarizes the estimates of potential future demand for CFCs from all the authors. The exhibit is divided into short-run and long-run estimates. The short-run estimates are divided into aerosol applications of CFC-11 and CFC-12, nonaerosol applications of CFC-11 and CFC-12, nonaerosol applications of HCFC-22, and nonaerosol applications of CFC-113. Within each of these categories, projections of future demand for various portions of the world are listed.

The long-term estimates portion of the exhibit reports on all the applications of CFC-11 and CFC-12 for the entire world. The uncertainties in these long-term estimates are listed. Exhibit 3-17 shows the long term projections made.

The short-term projections listed in Exhibit 3-16 show distinct themes. Aerosol applications of CFCs are expected to decline or remain constant in several portions of the world (EEC, U.S., Sweden). The growth in aerosol applications in other portions of the world is generally expected to be slight (Japan, 1.5 percent per year, and "Western" Countries, an average of less than 1.0 percent per year). Gibbs (1986a) reports a large rate of increase for the non-U.S. use of CFC-11 and CFC-12 in aerosols, but his aerosol estimates are higher than the other authors' estimates and are not considered representative of the overall aerosol projections.

These projections of aerosol applications also indicate an important point. Since the middle 1970s, the total use of CFCs in the Western Countries category (including the U.S.) has declined and remained fairly flat. This decline and subsequent flattening out of total use was driven by substantial reductions in aerosol applications, which balanced off increases in nonaerosol applications

EXHIBIT 3-15

Summary of Demand Projection Estimates

	BEVINGTON	CAMM	EFCTC	GIBBS	HAMMITT	OSTMAN	KNOLLYS	KUROSAWA	NORDHAUS	PERSKY	SHEFFIELD
COMPOUNDS COVERED:											
AEROSOL APPLICATIONS:											
CFC-11	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO
CFC-12	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO
NONAEROSOL APPLICATIONS:											
CFC-11	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES
CFC-12	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES
CFC-22	NO	NO	NO	YES	NO	NO	NO	NO	NO	NO	YES
CFC-113	YES	YES	NO	YES	YES	YES	.NO	NO	NO	NO	YES
REGIONS COVERED:	EEC	WORLD a/	VARIOUS b/	WORLD c/	WORLD a/	SWEDEN	EEC	JAPAN	WORLD d/	U.S.	CANADA
PERIOD COVERED:		e/									
SHORT TERM	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
LONG TERM	NO	YES	NO	YES	NO	NO	NO	NO	YES	NO	NO
METHOD USED:	BOTTOM UP	MIX e/	BOTTOM UP	TOP DOWN	BOTTOM UP	BOTTOM UP	BOTTOM UP	BOTTOM UP	TOP DOWN	TOP DOWN	TOP DOWN

a/ Camm and Hammitt break their world estimates into the following regions: (1) U.S.; (2) Other Reporting Countries; and (3) "Communist" Countries.

b/ Regions covered by EFCTC include: (1) Western Europe, South Africa, Australia, and New Zealand; and (2) the "Rest of the World," excluding North America (Canada, U.S., Mexico), Japan, East Bloc countries, and Peoples Republic of China.

c/ Gibbs reports results separately for: (1) U.S.; (2) non-U.S. OECD countries; and (3) the "Rest of the World."

d/ Nordhaus reports results separately for the U.S. and the Rest of the World.

e/ Camm's projections prior to 2000 are based on the bottom up approach results reported in Hammitt. The post-2000 estimates are based on the top down approach results reported in Quinn (1986).

Sources: Bevington 1986; Camm et al. 1986; EFCTC 1985; Gibbs 1986a; Hammitt et al. 1986; Ostman, Hedenstrom, and Samuelsson, 1986; Knollys 1986; Kurosawa and Imazeki 1986; Nordhaus and Yohe 1986; Persky, Weigel, and Whitfield 1985; Sheffield 1986 (see references for complete source).

EXHIBIT 3-16

Summary of Demand Projections

(Average annual rate of growth in percent)

	BEVINGTON	a/ CAMM	EFCTC	GIBBS	HAMMITT	OSTMAN	KNOLLYS	KUROSAWA	b/ NORDHAUS	PERSKY	SHEFFIELD
SHORT-TERM PROJECTIONS: APPROXIMATELY 1985 TO 1995/2000											
Aerosol Applications of CFC-11 and CFC-12:						c/					
EEC	-0.6	..	-0.6	0.0	-3.9	..	-0.6	..	..	..	..
Japan	..	..	..	..	..	..	..	1.5	..	..	..
Sweden	..	..	..	..	..	0.0	..	..	..	..	..
U.S.	..	..	..	0.0	0.0	..	..	..	..	..	..
"Western" Countries d/	..	..	0.2	2.5	0.1	..	..	..	..	..	..
World	..	..	..	4.0	1.7 e/	..	..	..	2.2	..	..
Nonaerosol Applications of CFC-11 and CFC-12:											
Canada	..	..	..	..	..	..	..	..	..	..	4.4-7.9
EEC c/	2.1	..	2.1	..	..	..	..	..	..	..	..
Japan	..	..	..	..	..	..	..	4.9	..	..	..
Sweden	..	..	..	..	..	4.2	..	..	..	..	..
U.S.	..	..	..	4.5	2.5	..	..	..	3.2	3.4	..
"Western" Countries d/	..	..	2.5	4.3	3.3	..	..	..	..	..	..
World	..	..	..	4.7	3.3 e/	..	..	..	3.7	..	..
Nonaerosol Applications of CFC-22:											
Canada	..	..	..	..	..	..	..	..	..	..	4.2-5.1
World	..	..	..	5.1	..	..	..	..	..	..	..
Nonaerosol Applications of CFC-113:											
Canada	..	..	..	..	..	..	..	..	..	..	4.5-8.9
EEC	7.5	..	..	..	..	..	..	..	..	..	..
Sweden	..	..	..	..	..	2.5	..	..	..	..	..
U.S.	..	..	..	5.3	5.9	..	..	..	..	..	..
"Western" Countries d/	..	..	..	5.3	7.1	..	..	..	..	..	..
World	..	..	..	5.4	6.5	..	..	..	..	..	..

.. = Not reported. Only "base case" or "middle" values are listed here for Camm, Gibbs, and Nordhaus.

EXHIBIT 3-16 (Continued)

Summary of Demand Projections
(Average annual rate of growth in percent)

	BEVINGTON	a/ CAMM	EFCTC	GIBBS	HAMMITT	OSTMAN	KNOLLYS	KUROSAWA	b/ NORDHAUS	PERSKY	SHEFFIELD
				LONG-TERM PROJECTIONS: APPROXIMATELY 2000 TO 2050							
All Applications of CFC-11 for the World:											
Lower Bound	..	0.5	..	1.8	..	..	..	..	..	..	..
Low	..	1.6	..	2.4	..	..	..	..	0.8	..	..
Medium	..	2.4	..	3.1	..	..	..	..	3.6	..	..
High	..	3.2	..	3.4	..	..	..	..	3.6	..	..
Upper Bound	..	4.3	..	4.0	..	..	..	..	..	..	..
All Applications of CFC-12 for the World:											
Lower Bound	..	-0.4	..	1.6	..	..	..	..	..	..	..
Low	..	1.6	..	2.0	..	..	..	..	1.0	..	..
Medium	..	2.4	..	2.6	..	..	..	..	3.6	..	..
High	..	3.2	..	2.8	..	..	..	..	3.9	..	..
Upper Bound	..	4.4	..	3.4	..	..	..	..	..	..	..

a/ Camm's short-term projections are based on Hammitt, and are therefore not listed here separately.

b/ Values listed under long-term projections are for the 25th, mean, and 75th percentile.

c/ EFCTC projection includes Western Europe, South Africa, Australia, and New Zealand.

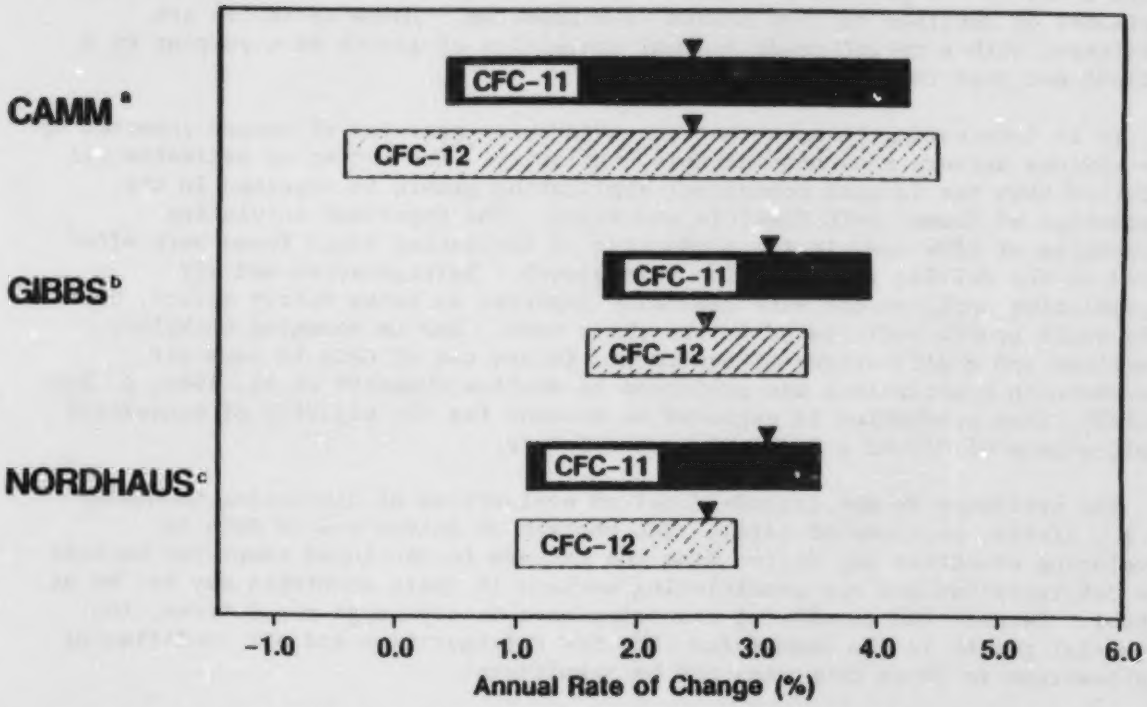
d/ Coverage varies by author. Approximate coverage includes non-U.S., non-East Bloc countries. EFCTC also excludes Japan, Canada, Mexico.

e/ Assumes that one-half of East Bloc country use reported in Hammitt is in aerosol applications.

Sources: Bevington 1986; Camm et al. 1986; EFCTC 1985; Gibbs 1986a; Hammitt et al. 1986; Ostman, Hedenstrom, and Samuelsson, 1986; Knollys 1986; Kurosawa and Imazeki 1986; Nordhaus and Yohe 1986; Persky, Weigel, and Whitfield 1985; Sheffield 1986 (see references for complete source).

EXHIBIT 3-17

Long Term Projection
CFC-11 and CFC-12 -- World Production
(2000-2050)



Source: "Overview Paper for Topic #2: Projections of Future Demand," UNEP Workshop, May 1986.

during this time. The projections of flat or slight growth for aerosol applications in the Western Countries indicate that: (1) as aerosol applications become a smaller share of total use, further aerosol application reductions will be less effective in balancing off growth in nonaerosol applications; and (2) future large reductions in aerosol applications are not anticipated under current regulations. Together, these two points indicate that the total use of CFC-11 and CFC-12 will increasingly be driven by expected rates of growth in nonaerosol applications.

The short-term nonaerosol applications of CFC-11 and CFC-12 show a trend that is different than the trend for aerosol applications. All estimates indicate continued strong growth in nonaerosol applications during the short term. The estimates range from 2.1 percent per year in the EEC (Bevington 1986; EFCTC 1985) to 7.9 percent per year in Canada (Sheffield 1986, upper bound). No estimates of declines or flat demand were reported. These estimates are consistent with a recent trade journal projection of growth of 4 percent to 5 percent per year through 1990.[5]

It is interesting to note that the underlying patterns of demand reported by the various authors show considerable similarity. The bottom up estimates all reported that the largest nonaerosol application growth is expected in the production of foams, both flexible and rigid. The important insulating properties of CFCs used in the production of insulating rigid foams were often cited as the driving factor behind this growth. Refrigeration and air conditioning applications were generally reported as being fairly mature, with only small growth anticipated in the short term. Due to changing workplace practices and modifications to equipment, future use of CFCs in some air conditioning applications was projected to decline (Hammitt et al. 1986, p. 56). Overall, foam production is expected to account for the majority of nonaerosol applications of CFC-11 and CFC-12 in the future.

The estimates do not include detailed evaluations of developing countries (e.g., Africa, portions of Asia). The pattern of future use of CFCs in developing countries may differ from the pattern in developed countries because the refrigeration and air conditioning markets in these countries may not be as mature. Because the developing countries have fairly large populations, the potential growth in the demand for CFCs for refrigeration and air conditioning applications in these countries may be significant.

The several estimates of future demand for HCFC-22 and CFC-113 are also shown in Exhibit 3-16. All estimates show strong growth. The demand for CFC-113 is reportedly driven by expected strong growth in solvent applications, particularly in solvents used for cleaning electronic components. Although these CFCs are expected to grow rapidly in the short term, their overall level of use will remain well below the level of use of CFC-11 and CFC-12 (less than half).

Exhibit 3-16 also displays long-term demand projections by Camm et al., Gibbs, and Nordhaus and Yohe. These projections are necessarily more uncertain than the short-term estimates, and consequently the full range of estimates provided by each author is listed. As one check on the validity of these long-term projections, one should note that in the short term (through 2000) they are consistent with the range of short-term estimates provided by the other authors.

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[5] Chemical Marketing Reporter, March 10, 1986, p.54.

As shown in Exhibit 3-16, the overall picture of long-term demand for CFCs is one that may range from modest growth (on the order of 1.0 percent per year or less), to sustained strong growth (nearly 4.0 percent per year). The only possibility that appears to have been considered unlikely by the authors is substantial declines in the use of CFCs over the long term. As the authors caution, however, currently unforeseen technological advances could produce a situation where use declines (or increases) considerably, as unforeseen applications develop. Although the likelihood of either a considerable decline or increase is difficult to quantify at this time, it is believed to be very small.

The specific methods used by the individual authors varied. Each paper is summarized in turn.

Bevington (1986): Projections of Production Capacity, Production and Use of CFCs in the Context of EEC Regulations.

Bevington presents projections for the demand of CFC-11, CFC-12, CFC-113, and CFC-114 in EEC countries from 1984 to 1995. The bottom up approach was used, with various trade associations providing estimates of expected rates of growth in particular product markets (associations listed include: EFCTC; FEA; BING; and EUROPUR). Products examined include: aerosols; rigid foams; flexible foams; solvents; and other.

Exhibit 3-18 summarizes Bevington's projections for the EEC. Aerosol applications of all the CFCs are projected to continue to decline. The most rapidly growing nonaerosol applications of CFC-11 and CFC-12 are expected to be foams (both rigid and flexible). Refrigeration applications are expected to grow more slowly, and are projected to account for less than 12 percent of CFC-11 and CFC-12 use by 1995.

The CFC-113 and CFC-114 use is dominated by the solvent applications of CFC-113. Use in this application is projected to grow significantly over the period examined, producing an average increase of 6.7 percent per year for all CFC-113 and CFC-114 uses.

Camm et al. (1986): Joint Emission Scenarios for Potential Ozone Depleting Substances.

Camm presents projections of the demand for seven potential ozone-modifying substances: CFC-11; CFC-12; CFC-113; methyl chloroform; carbon tetrachloride; Halon-1301; and Halon-1211. This summary includes only the CFCs. A range of projections are provided for the entire world and for two time periods: 1985 to 2000 and 2000 to 2040. The projections are based on scenarios of potential future demand developed using the bottom up approach for 1985 to 2000 reported in Hammitt (1986) and the top down approach for 2000 to 2040 reported in Quinn (1986). The range of projections in both the short and long term reflect uncertainties in the rate of economic growth and the role that CFCs will play

EXHIBIT 3-18

BEVINGTON'S PROJECTIONS FOR USE OF CFCs IN THE EEC
(Annual average rate of change for 1984 to 1995)

	RATE OF CHANGE (%)
CFC-11 and CFC-12:	
Aerosol Applications	-0.6%
Nonaerosol Applications	2.1%
Total	0.8%
CFC-113 AND CFC-114:	
Aerosol Applications	-0.6%
Nonaerosol Applications	7.5%
Total	6.7%

Source: Bevington (1986), p. 10-11.

in its various applications. Exhibit 3-19 summarizes the projections of global demand for each of the compounds individually. A total of five estimates are presented for each compound, for each time period.

As shown in the exhibit, CFC-113 is projected to grow the fastest, followed by CFC-11, and then CFC-12. The range between the Low and High scenarios is estimated by Camm to reflect a 50 percent confidence interval (i.e., the likelihood of the result actually falling in this range is estimated as 0.5). The range between the Lower Bound and the Upper Bound is reportedly a 90 percent confidence interval. The base case economic growth rate assumptions are 3.3 percent per year for the period 1985 to 2000 and 2.4 percent per year for 2000 to 2040.

Comparing these growth rate assumptions to the values in Exhibit 3-19 indicates that: the use of CFC-11 is expected to grow at approximately the rate of economic growth in the Medium case in both the short and long term; the use of CFC-12 is expected to grow more slowly than the rate of economic growth through 2000, and at approximately the rate of economic growth after 2000; and the use of CFC-113 is expected to grow more rapidly than economic growth through 2000, and at approximately the rate of economic growth after 2000. The range of uncertainty includes growth of all the chemicals both exceeding or being less than the rate of growth in economic activity.

The differential patterns of growth and decline across various applications and regions of the world are not reported in Camm. However, the detailed projections in Hammitt (summarized separately), upon which the Camm estimates prior to 2000 are based, indicate that patterns vary across uses and regions of the world. The estimates for post-2000 are based on top down estimates from Quinn (1986), which do not explicitly report changing mixes of CFC applications.

The work by Camm makes an important contribution to the development of scenarios of future demand because it not only provides detailed scenarios of the future use of each of the CFCs, but it is the only method that attempts to reflect a convolution of uncertainties across chemical compounds. Camm correctly asserts that taking the fifth fractile estimate of demand for each potential ozone-depleting substance at the same time does not necessarily produce the fifth fractile estimate of ozone-depleting potential. Because ozone-depleting potential is the key policy variable of interest, Camm et al. developed a method for identifying joint scenarios across a group of compounds that convolute each compound's uncertainties in conjunction with each compound's ozone-depletion potential.

The results of this approach for creating joint scenarios are scenarios of chemical production that have narrower uncertainties than the independent scenarios for each compound (reported in Exhibit 3-19). This result is expected when the uncertainty across compounds is not perfectly correlated (a reasonable assumption). The degree of correlation among the uncertainties is unknown, and the Camm assumption of complete independence across the chemicals (except for the common driving factor of economic growth) may be extreme. Nevertheless, the general result of their work is indicative that the scenarios of production used for policy analysis should possibly be narrower in uncertainty than the scenarios estimated for each compound separately.

EXHIBIT 3-19

CAMM PROJECTIONS OF WORLD USE
(Annual average growth rate in percent)

Chemical	Period	Lower Bound	Low	Medium	High	Upper Bound
CFC-11	1985-2000	0.81	2.27	3.29	4.31	5.78
	2000-2040	0.47	1.61	2.40	3.19	4.33
CFC-12	1985-2000	-0.29	1.21	2.27	3.32	4.83
	2000-2040	-0.43	1.59	2.40	3.21	4.37
CFC-113	1985-2000	1.19	5.19	6.55	7.93	9.89
	2000-2040	-0.06	1.39	2.40	3.41	4.86

Source: Camm (1986).

European Fluorocarbon Technical Committee (EFCTC) (1985), Halocarbon Trend Study 1983-1995.

The EFCTC provides projections of the consumption of CFC-11 and CFC-12 for the following uses: aerosols; refrigeration; rigid foam; flexible foam; and other (food freezant, sterilizing gas, fire-fighting chemicals, vapor-pressure control instruments, wind tunnels, solvent applications, and flotation processes). The projections cover the period 1983 to 1995 and are divided into two regions: (1) Western Europe, South Africa, Australia and New Zealand; and (2) "Rest of World," excluding: North America (U.S., Canada, Mexico), Japan, East Bloc countries, and Peoples Republic of China.

The bottom up approach was used to prepare these forecasts. Forecasts were made by individual CFC producers, and collated and averaged in a confidential manner. Each projection was weighted equally, and the average was adopted by the EFCTC as "representing the best view of the European CFC producers on the future use of chlorofluorocarbons 11 and 12" (p. 1). Exhibit 3-20 summarizes the EFCTC projections for the two regions identified above.

As shown in Exhibit 3-20, aerosol use is projected to increase slightly for CFC-11 and decrease slightly for CFC-12. Nonaerosol applications of both CFCs are projected to grow between two and three percent per year.

Gibbs (1986): Scenarios of CFC Use: 1985 to 2075.

Gibbs presents scenarios of the potential future use of CFC-11, CFC-12, HCFC-22, and CFC-113 in aerosol and nonaerosol applications. Estimates are provided for four time periods (1985-2000; 2000-2025; 2025-2050; and 2050-2075) and for three parts of the world (U.S.; non-U.S. OECD; and the Rest of the World).

Gibbs developed relationships between per capita CFC usage and per capita GNP based on historical data, controlled for the price of CFCs, and included estimates for OECD countries. Ordinary least squares regression was used, and serial correlation reportedly biased downward the estimates of the standard deviations of the coefficients.

Gibbs applied these relationships to the OECD countries using a range of population and GNP scenarios from published sources. The ranges used were quite large, resulting in wide ranges of potential CFC demand in the future. Population varied by a factor of nearly two by 2075, and GNP per capita varied by nearly a factor of five. Gibbs' population and GNP scenarios are summarized in Exhibit 3-21. In his highest and lowest scenarios, Gibbs also adjusted the coefficients by one standard deviation to reflect potential technological innovation. The potential implications of innovation were not explicitly evaluated.

Gibbs estimated demand in the non-OECD countries by assuming that per capita demand in these countries by the end of the projection period (2075) would be the ratio of (1) the GNP per capita in the non-OECD countries to (2) the current GNP per capita in the OECD countries times the current use per

EXHIBIT 3-20

SUMMARY OF EFCTC PROJECTIONS

	ANNUAL AVERAGE RATE OF CHANGE (%)		
	1983-1990	1990-1995	1983-1995
CFC-11 CONSUMPTION			
Aerosol Applications	0.4%	0.4%	0.4%
Nonaerosol Applications	2.5%	2.1%	2.3%
Total CFC-11	1.6%	1.4%	1.5%
CFC-12 CONSUMPTION			
Aerosol Applications	-0.1%	0.2%	0.0%
Nonaerosol Applications	2.7%	2.9%	2.8%
Total CFC-12	1.4%	1.7%	1.5%

Source: EFCTC (1985) Appendix IV.

EXHIBIT 3-21

Global Population and GNP Scenarios Used in Gibbs' Analysis

GLOBAL POPULATION SCENARIOS (millions)

Year	Lowest	Low	Medium	High	Highest
1985	4536	4745	4745	4835	5000
2000	5377	5901	5901	6147	6500
2025	6505	7384	7384	8160	9500
2050	7324	7664	8223	9496	12100
2075	7131	7944	8491	9960	13600

GLOBAL GNP PER CAPITA SCENARIOS (1975 U.S. $)

Year	Lowest	Low	Medium	High	Highest
1985	1900	1900	1900	1900	1900
2000	2206	2375	2447	2557	2752
2025	2499	3201	3729	4195	5102
2050	2831	4105	5683	6883	9458
2075	3051	5264	8662	11292	17535

Source: Gibbs, Michael J. (1986), Scenarios of CFC Use: 1985 to 2075, ICF Incorporated, prepared for U.S. Environmental Protection Agency, Washington, D.C.

capita in the OECD countries. Between 1985 and 2075 Gibbs fitted an "S-shaped" curve that reflects the standard product lifecycle.

This method of projecting non-OECD demand has a large influence on the overall results produced by Gibbs because the non-OECD countries account for a large fraction of the total growth in demand (nearly 50 percent). The potential bias of the method is ambiguous. Differences between the OECD and non-OECD countries (in terms of culture, climate, and other factors) could produce different patterns of CFC use relative to OECD countries, even at similar levels of per capita GNP. Whether the levels would be higher or lower, is unknown.

There is some indication that Gibbs' method may produce estimates of demand in the non-OECD countries that are biased downward, because evidence indicates that at the same level of income per capita, later developing countries tend to have higher levels of consumption of industrial products when compared to the countries that developed first. The explanation given is that product penetration into the market place generally proceeds faster in later developing countries. Whether this would be the case for CFCs in non-OECD countries is unknown, although evidence indicates it may have been true in the non-U.S. OECD countries as compared to the U.S.[6]

Gibbs presents five scenarios of future demand that reflect a wide range of assumptions about the potential future rates of growth in GNP per capita and population. The scenarios were not adjusted to reflect potential changes in the structure of the CFC markets. Exhibit 3-22 presents the Gibbs scenarios for the entire world, for both aerosol and nonaerosol applications.

As shown in the exhibit, each of the compounds is expected to grow more rapidly in the short term than in the long term. CFC-113 is projected to grow most rapidly, followed by HCFC-22, CFC-11 and then CFC-12. Compared to the assumed growth rates for global GNP, the scenarios display CFC growth in excess of economic growth for all the scenarios; the increment over the rate of economic growth is lower in the long term.

The overall patterns of growth shown in Exhibit 3-22 include differential rates of growth of aerosol and nonaerosol applications in different regions of the world. In the U.S. and EEC countries, aerosol use is assumed to remain constant throughout the period examined. Aerosol applications in other regions are permitted to grow. Nonaerosol applications are projected to grow at rates that exceed the assumed rates of economic growth in all regions. The analysis by Gibbs does not incorporate assumptions about specific nonaerosol uses of CFCs. Also, confidence intervals or probabilities are not assigned to Gibbs' scenarios. Consequently, although a range is presented, the likelihood of future demand falling in particular portions of the range cannot be computed.

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[6] Gibbs (1986b), p. 17.

EXHIBIT 3-22

GIBBS SCENARIOS OF WORLD CFC USE
(Annual average growth in percent)

Chemical	Period	Lower Bound	Low	Medium	High	Upper Bound
CFC-11	1985-2000	3.2	4.0	4.5	5.6	6.5
	2000-2075	1.8	2.4	3.1	3.4	4.0
CFC-12	1985-2000	2.8	3.7	4.4	6.0	6.7
	2000-2075	1.4	2.0	2.6	2.8	3.4
HCFC-22	1985-2000	4.1	4.7	5.1	6.2	6.7
	2000-2075	1.2	1.8	2.6	2.9	3.6
CFC-113	1985-2000	4.1	5.0	5.4	6.4	7.0
	2000-2075	1.1	1.7	2.5	2.9	3.6
GNP	1985-2000	2.1	2.9	3.1	3.5	4.1
GROWTH	2000-2075	0.8	1.5	2.2	2.7	3.5

Source: Gibbs (1986) Exhibit 8, and Exhibit E-2.

Hammitt et al. (1986): Product Uses and Market Trends for Potential Ozone Depleting Substances: 1985-2000.

Hammitt presents projections of the use of seven potential ozone-modifying substances: CFC-11; CFC-12; CFC-113; methyl chloroform; carbon tetrachloride; Halon 1301; and Halon 1211. This summary includes only the CFCs. The projections are developed for the period 1985 to 2000 using the bottom up approach and the following CFC applications: aerosol propellants; rigid foams; flexible foams; refrigeration and air conditioning; miscellaneous uses of CFC-11 and CFC-12 (sterilants, fast food freezing, other); and solvents (CFC-113 only). Each application is examined in detail, and projections are presented separately for the following three regions: U.S.; other "non-communist" countries (referred to in the report as other countries that report production to the Chemical Manufacturers Association); and "communist" countries.

The base case Hammitt projections for the world are presented in Exhibit 3-23 along with upper and lower bounds. As shown in the exhibit, CFC-113 is anticipated to grow most quickly during this period, averaging 6.5 percent per year in the base case. CFC-11 has a base case estimate of 3.3 percent per year, and CFC-12 has a base case estimate of 2.3 percent.

Within these global figures, some applications are expected to decrease in their use of CFCs (e.g., aerosol applications of CFCs in EEC countries), some are expected to remain approximately constant (e.g., aerosol applications in the U.S.), and some are expected to increase (e.g., solvent applications of CFC-113 and CFC-11 and CFC-12 foam blowing applications). Patterns of change are not uniform across all portions of the world. In total, however, global use in relation to global economic growth (assumed in the study to be 3.3 percent per year in the base case) is expected to be as follows:

- CFC-11: 40 percent to 160 percent of base economic growth, with a base case of 100 percent of economic growth.
- CFC-12: 9 percent to 130 percent of base economic growth, with a base case of 70 percent of economic growth.
- CFC-113: 120 percent to 280 percent of base economic growth, with a base case of 200 percent of economic growth.

These ranges of uncertainty reportedly reflect an 80 percent confidence interval (meaning that the actual result is expected to fall in this range with a likelihood of 0.8), and include the possibility of economic growth being higher or lower than the base case. Additionally, they reflect the potential for technological change and changing market structure.

The Hammitt paper is the only one reviewed that explicitly considered the potential implications of technological innovation in a detailed manner. Additionally, the explicit quantification of uncertainty provides guidance as to the likelihood of the different scenarios. The shortcomings of the method are that:

- it was unable to associate all current production with an application -- a significant portion of production remained unallocated across applications, implying

EXHIBIT 3-23

HAMMITT PROJECTIONS OF WORLD CFC USE
(Average annual growth rate for 1985 to 2000 in percent)

	Base Case	Lower Bound	Upper Bound
CFC-11	3.3%	1.4%	5.2%
CFC-12	2.3%	0.3%	4.5%
CFC-113	6.5%	3.9%	9.2%

Source: Hammitt (1986), Table S.1.

that better information on specific uses could be obtained, and that the method may underestimate future demand; and

- the assumption of normally-distributed uncertainty may be unrealistic, given evidence from the results by Nordhaus and Yohe that indicate that a skewed result may be possible.

Ostman, Hedenstrom and Samuelsson (1986): Projections of CFC Used in Sweden.

Ostman provides a detailed bottom up analysis of CFC-11, CFC-12, and CFC-113 uses in Sweden. Recent and ongoing trends in current uses and technologies are described. Special attention is paid to expected changes in these trends, including saturation in key markets or applications that have grown rapidly in the past. Projections are provided for the period 1984 to 1994 covering the following uses: flexible foams; rigid foams (polyurethane in refrigerators/cooling and other, and extruded polystyrene); cooling and heating (cooling, service, heat pumps, heat pump service); degreasing and cleaning; and other. Of note is that projections are reported for the use on CFCs in these products that are consumed in Sweden, including products that are imported into Sweden.

Exhibit 3-24 summarizes Ostman's projections across all the uses examined (including net imports). Overall, strong growth is projected for total CFC-11 and CFC-12 use. The largest growth is projected in rigid foams, particularly extruded polystyrene. These foams are used as "insulation in houses, insulation in the ground and packaging material" (p. 11). "Despite the low new production activity within the building industry an increase in insulation and panel demand is expected" (section 4). These foams account for over 75 percent of the increase in CFC-11 and CFC-12 use projected between 1984 and 1994.

Modest growth is projected for heating and cooling applications, mostly in the area of service. New installations are not expected to grow significantly because these markets are well saturated. The authors note that recovery of CFCs during service could have a "marked effect on the emissions of CFCs from this sector" (p. 12).

As shown in Exhibit 3-24, CFC-113 is also expected to increase in use, although not as rapidly as CFC-11 and CFC-12. Ostman reports that CFC-113's "... higher prices (compared to possible substitutes) are holding them back and for larger consumers of degreasing agents for more "general" purposes they are not yet attractive" (p. 13). Also noted is the possibility that CFC-113 growth could be larger if its substitutes are subjected to further health restrictions.

This study is distinguished as the only regional study that explicitly estimated the amount of CFCs contained in products that are imported and exported. CFCs are imported to Sweden in bulk as well as in finished products (such as refrigerators). Sweden does not produce CFCs.

EXHIBIT 3-24

SUMMARY OF HEDENSTROM PROJECTIONS FOR SWEDEN
(Average annual rate of growth for 1984-1994)

	GROWTH RATE (%)
CFC-11 and CFC-12	4.1%
Nonaerosol applications	4.2%
Aerosol applications	0.0%
CFC-113	2.5%

Source: Hedenstrom (1986), Table 3.

Not included in the Ostman study (or in any other study) are the regional CFC demand implications of trade in products that do not retain their CFCs after manufacture (e.g., flexible urethane foam). The methods generally used for estimating demand for CFCs assigns the demand to the country of manufacture of the foam, not to the country that uses the foam. The extent to which the incorporation of this factor would modify the current perception of regional CFC demand is not known at this time. Flexible foam products (cars, furniture) and electronic components (cleaned with CFC-113 solvent) are traded extensively on the world market.

Knollys (1986): Fluorocarbon Use in Aerosols -- A Trend Study 1984-1995 in Member Countries of the European Economic Community.

Knollys projects the use of CFCs in aerosols in the member countries of the EEC from 1984 to 1995. Although not explicitly stated, it is assumed for this summary that the projection applies to CFC-11 and CFC-12. The bottom up method was used, where "member associations representing the aerosol industries in countries in the European Economic Community ... prepare(d) forecasts of aerosol production for the years 1990 and 1995 and ... compare(d) these with actual production estimates for 1984" (p. 14). Forecasts covering 13 separate aerosol categories were received from countries that represent 54 percent of 1984 EEC production. To create an aggregate forecast, these forecasts were adjusted to reflect the share that these countries have of the market for each of the product categories, and then aggregated. From the data presented it is not possible to identify the range of coverage within each of the 13 categories.

The projection provided by Knollys is summarized in Exhibit 3-25. As shown, EEC aerosol production is expected to increase, as is the quantity of the contents of the aerosol packages. However, the amount of CFCs in the packages is expected to decrease by an average of 0.75 percent per year from 1984 to 1990, and by 0.40 percent per year from 1990 to 1995. The explicit factors driving these results are not reported.

Of the 13 categories analyzed, only two are projected to have declines in aerosol production packs and contents between 1984 and 1995 (hairspray and insecticides). The other 11 categories are projected to have increases (hair mousse, deodorant/anti-perspirant, body spray, shave foam, household cleaners, air fresheners, automotive products, industrial products, paint, food, and others). In terms of CFC propellant use in aerosols, only four categories are projected to have increases (shave foam, automotive products, industrial products, and others). These four categories account for 24.5 percent of aerosol propellant applications in 1984, and are projected to increase by less than one percent per year from 1984 to 1995.

Assumptions regarding economic growth are not reported, so it is not possible to relate these projections to future growth. Although the uncertainty of the projection is not quantified, Knollys states that the general direction of the trend is reasonable (p. 15).

EXHIBIT 3-25

KNOLLYS PROJECTIONS

	ANNUAL AVERAGE RATE OF CHANGE (%)		
	1984-1990	1990-1995	1984-1995
EEC AEROSOL PRODUCTION (Packs)	1.3%	1.6%	1.4%
EEC AEROSOL PRODUCTION (Contents)	1.1%	1.1%	1.1%
EEC USE OF CFCs IN AEROSOLS	-0.75%	-0.4%	-0.6%

Source: Knollys (1986), tables 4, 5, and 6.

Kurosawa Imazeki (1986): Projections of the Production Use and Trade of CFCs in Japan in the Next 5-10 Years.

Kurosawa provides projections for CFC-11 and CFC-12 production in Japan for 1985 to 1995 for the following uses: refrigerant; aerosol propellant; blowing agent; and export. The bottom up approach was used, with the prospects for continued development in these products and exports examined individually. As shown in Exhibit 3-26, growth is anticipated throughout the period. Blowing agents account for most of the projected growth in production between 1985 and 1995 (51 percent); refrigerants account for 32 percent of the growth; exports account for 12 percent; and aerosols account for 5 percent.

The blowing agent growth is reportedly driven by increases in the production of automobiles. Refrigeration uses are driven by the demand for building air conditioners, automobile air conditioners, and demand for refrigerators for export. Kurosawa reports that CFCs in aerosol propellant applications (expected to grow slightly) "have become an essential element as a flammability suppressant" (p. 3). Finally, exports from Japan to its East and Southeast Asian neighbors are expected to increase because these nations do not currently produce CFCs.

Nordhaus and Yohe (1986): Probabilistic Projections of Chlorofluorocarbon Consumption: Stage One.

The approach used by Nordhaus, called probabilistic scenario analysis, explicitly considers uncertainty and is based on statistical analyses of historical data. This method was originally designed by the authors to investigate the problem of forecasting carbon dioxide emissions and concentrations from an economically consistent model of future energy markets. The method provides not only a best-guess estimate, but a quantified range of uncertainty, built up from uncertainty regarding the individual factors affecting demand.

Using statistical methods and historical data, Nordhaus and Yohe specified the relationship driving the intensity of use of CFC-11 and CFC-12 over time in the U.S. A family of logistic curves is fit to the data to describe the manner in which the use of CFCs approaches what is called a "frontier" over time. The frontier represents the total possible use of CFCs at a given level of wealth, and it changes over time. A family of curves is used to represent the uncertainty in the location of the frontier, which is not known with precision.

This method is able to capture the implicit effects of product introduction, innovation, and maturity. It reflects the uncertainty in our ability to estimate (from historical data) the relative importance of these factors. Because data are not available for performing this analysis on the rest of the world outside the U.S., the authors assume that the rest of the world will develop in a pattern similar to the lead provided by the U.S., but more slowly.

The relationships developed using this method are used to project future demand. First, the basic building blocks of the relationships, the rate of change of the frontier, the increase in labor productivity, and population

EXHIBIT 3-26

SUMMARY OF KUROSAWA PROJECTIONS FOR JAPAN
(Average annual rate of growth 1985-1995)

	RATE OF GROWTH (%)
CFC-11 and CFC-12	4.4%
Nonaerosol applications	4.9%
Aerosol applications	1.5%
Exports	6.1%

Source: Kurosawa (1986), Table 1.

growth are projected. The future values for labor productivity and population are derived from probability distributions. The distributions are based on the range of published estimates, and studies that indicate that ranges of published estimates often understate true uncertainty. As recognized by the authors, however, the distributions are considered to be subjective.

Estimates of the future growth or decline of the frontier for CFC use have not been published. Nordhaus and Yohe write that a reasonable range for industrially demanded goods is between a 2 percent per year average decline to a 2 percent per year average increase. A decline in the frontier implies that the amount of CFCs that can be used at a given level of economic activity (e.g., measured as gross national product or GNP) is declining over time. In other words, due to technological innovation, product displacement, or other factors, the intensity with which CFCs would be used per dollar of GNP is simulated to decrease. An increase in the frontier implies the opposite, an increase in intensity. This range of a 2 percent decrease to a 2 percent increase is used in the study.

Given the relationships based on historical data and the probability distributions for the future values for population, labor productivity, and the CFC frontier, a Monte Carlo analysis is performed by drawing from the distributions using pseudo-random numbers, and inserting the drawn values into the relationships. A number of independent trials are performed, the results of which form a distribution. This distribution of results reflects the uncertainty in each of the steps of the method.

The strengths of this approach include its statistical analysis of historical data and its explicit consideration and modeling of uncertainty. Of interest is that the results indicate that the potential for future demand for CFC-11 and CFC-12 does not have a symmetrical range of uncertainty. The possibilities for values that are much larger than the median appear to exceed the possibilities that the values will be far below the median. Also, there does not appear to be a significant likelihood that CFC-11 and CFC-12 demand will decrease from current levels (in the absence of regulation), even though a decline in the CFC frontier is modeled as being equally likely as an increase.

The shortcoming of the analysis is the lack of detail with which the use of CFCs is modeled in countries outside the U.S. Applying the U.S.-based relationships may over- or understate demand in these countries; the bias is ambiguous.

The nonaerosol results obtained by Nordhaus are presented in Exhibit 3-27. Estimates are provided for the 25th and 75th percentiles and for the mean. The percentile estimates may be interpreted as meaning that the result is expected to fall below the 25th percentile 25 percent of the time, between the 25th and 75th percentiles 50 percent of the time, and above the 75th percentile 25 percent of the time. The mean represents the average of all possible outcomes.

Exhibit 3-27 shows that CFC-11 is expected to grow more rapidly than CFC-12. Also, the rate of growth of both the CFCs exceeds the rate of economic growth in the near term for all the projections presented. In the long term (post 2000), the rate of growth in the consumption of the chemicals may be

EXHIBIT 3-27

NORDHAUS SCENARIOS OF WORLD NONAEROSOL CFC CONSUMPTION
(Annual average rate of growth in percent)

Compound	Period	25th Percentile	75th Percentile	Mean
CFC-11	1980-2000	3.2	5.4	4.6
	2000-2050	1.2	3.6	3.5
CFC-12	1980-2000	3.0	4.8	4.0
	2000-2050	1.1	2.9	3.1
ECONOMIC GROWTH	1980-2000	3.1	4.0	3.6
	2000-2050	1.7	2.5	2.2

Source: Nordhaus (1986) Table III-3 and Table III-4.

greater than (75th percentile and the mean) or less than (25th percentile) the rate of economic growth.

Persky, Weigel, and Whitfield (1985): A Review of the Study: "Projected Use, Emissions, and Banks of Potential Ozone Depleting Substances" (Rand Report No. 2483-3-EPA).

Persky examined the draft Rand Report Projected Use, Emissions, and Banks of Potential Ozone Depleting Substances by Quinn (1985), the revised version of which formed the basis for the long-term projections presented in Camm (1986). Persky raised questions regarding the data and assumptions used in Quinn (1985) and the model used to project future demand. In doing the review, Persky presented an alternative estimate of future demand for CFC-11 and CFC-12 in nonaerosol applications in the U.S. from 1985 to 2010. The top down approach was used, where historical CFC use in the U.S. was related to historical GNP per capita in the U.S. The projected growth rates were 3.5 percent per year and 3.4 percent per year for CFC-11 and CFC-12 respectively, for the period 1985 to 2010. The underlying assumptions about economic growth and population growth were not reported.

It should be noted that the focus of the Persky paper is a critique of Quinn (1985); its primary objective was not to develop an independent projection of CFC demand.

Sheffield (1986): Canadian Overview of CFC Demand Projections to the Year 2005.

Sheffield provides two projections of the potential nonaerosol use of CFC-11, CFC-12, HCFC-22, and CFC-113 in Canada from 1984 to 2005. A top down approach is used where CFC use per capita in several applications is related to GNP per capita and a time trend variable. The applications examined include: CFC-11 and CFC-12 in foams, CFC-11, CFC-12, and HCFC-22 in refrigeration, and CFC-113 in solvents. Two projections were developed: one using an exponential model to fit parameters to the historical data, and a second using a linear model. The exponential model produces much larger projections than does the linear model, and Sheffield states that "... we can rest reasonably assured that the actual use in the year 2005 will probably fall somewhere" between the two projections (p. 11).

Exhibit 3-28 displays the overall results reported by Sheffield. Strong growth is projected for all the compounds examined. Solvent applications of CFC-113 are anticipated to grow at the fastest rate. Foam applications of CFC-12 are projected to account for the largest share of future growth (22 to 58 percent, depending on the projection). Refrigeration applications display the slowest rates of growth.

Despite the diversity of the methods used by the various authors to project possible future demand, the results presented above indicate a considerable degree of similarity and consensus. The overall picture of long-term demand for CFCs is one that may range from modest growth (on the order of 1.0 percent per year or less) to sustained strong growth (nearly 4.0 percent per year). The only possibility that appears to have been considered

EXHIBIT 3-28

SUMMARY OF SHEFFIELD PROJECTIONS FOR CANADA 1984-2005
(Annual average growth rates in percent)

COMPOUND	LINEAR MODEL	EXPONENTIAL MODEL
CFC-11	4.4%	6.4%
CFC-12	4.4%	8.5%
HCFC-22	4.2%	5.1%
CFC-113	4.5%	8.9%

Source: Sheffield (1986), p. 16.

unlikely by the authors is substantial declines in the use of CFCs over the long term.

Of note is that potential constraints on future production were investigated in two studies, Gibbs and Weiner (1986) and Mooz, Wolf, and Camm (1986). Both studies investigated the potential for the supply of fluorspar to constrain future CFC production. Fluorspar is the primary source of fluorine used in the production of hydrofluoric acid (HF), which is used to make CFCs. It is considered a strategic mineral because it is also used in the production of steel, and HF is also used to make aluminum. Although not mined extensively in the U.S., fluorspar is abundant in Mexico, South Africa, China, Mongolia, and portions of Southeast Asia (Gibbs and Weiner 1986).

To assess whether fluorspar availability would likely constrain future CFC production, Gibbs and Weiner and Mooz, Wolf and Camm compared U.S. Bureau of Mines estimates of fluorspar resources to the potential requirements of future production implied by the demand scenarios developed in Gibbs (1986a) and Camm et al. (1986). Both studies found that currently identified economic reserves would be sufficient to supply expected fluorspar demand (from all applications) for the next 20 years. The high quality of the ore currently being mined (e.g., in Mexico and Southeast Asia) and the fact that fluorspar has historically been abundant indicate that it is likely that sufficient new reserves will be available to meet demand far beyond the next 20 years. Gibbs and Weiner found that the rate at which new reserves would have to be added in order to meet demand over the next 65 to 90 years was less than the rate of addition to reserves over the last 20 years. Additionally, Mooz, Wolf, and Camm point out that the abundance of fluorine in other forms (such as phosphate rock) could provide a potentially large source of fluorine. However, it is expensive to recover fluorine from these sources.

Mooz, Camm, and Wolf also examined possible constraints posed by the availability of production capacity. Although current production capacity may be reached by approximately the year 2000, they found that in the absence of government regulation, increases in capacity would likely take place.

These two studies indicate, therefore, that currently there do not appear to be supply constraints that would limit the ability to meet the future demand for CFCs.

CHLOROCARBONS

Two chlorocarbons have been identified as potentially important ozone depleters:

- carbon tetrachloride (CCl4); and
- methyl chloroform (CH3CCl3).

Carbon tetrachloride is an excellent solvent in many applications, and was once used extensively as a solvent and grain fumigant in the U.S. Because of its toxicity, it is only used in small amounts in such applications today (Hammitt et al. 1986). The major use of carbon tetrachloride in the U.S. is in the manufacture of CFC-11 and CFC-12. During the manufacturing process, almost all of the carbon tetrachloride is consumed or destroyed; very little is emitted.

Hammitt et al. (1986) estimate current U.S. production of carbon tetrachloride at 280 thousand metric tons, and world production at 870 thousand metric tons (this estimate does not include production in East Bloc countries). Hammitt et al. and Camm et al. project the future demand for carbon tetrachloride to remain closely tied to the demand for CFC-11 and CFC-12. Consequently, the future rates of growth in demand for of this compound are expected to be approximately the same as the rates of growth in the demand for these CFCs. Of note is that the uses of carbon tetrachloride as a solvent and grain fumigant may persist in other countries. The projections of demand for those compounds are therefore uncertain.

Methyl chloroform is produced in large quantities around the world, and is used as a cleaning solvent in vapor degreasing and cold cleaning applications. Small amounts are also used in adhesives, aerosols, and coatings (Hammitt et al. 1986). Hammitt et al. estimate 1985 U.S. production at 270 thousand metric tons and world production at 545 thousand metric tons (Hammitt et al. 1986, p. 80).

Hammitt et al. (1986) and Camm et al. (1986) estimate a range of future growth in the demand for methyl chloroform. These growth rates reflect alternative assumptions regarding the influence on use and recycling of the expected land disposal ban on chlorinated solvents (including methyl chloroform). These annual rates range from 0.4 percent to 4.7 percent for the period 1985 to 2040. Due to the lack of data on the production and use of methyl chloroform outside the United States, these estimates of production and emissions are recognized as uncertain.

HALONS

Halogenated extinguishing agents are made from hydrocarbons in which one or more hydrogen atoms have been replaced by halogen atoms. The common halogen elements are fluorine, chlorine, bromine, and iodine. These extinguishing agents include:

Chemical Name	Formula	Halon No.	Use
Methyl bromide	CH_3Br	1001	Fixed
Methyl Iodide	CH_3I	10001	
Bromochloromethane	$BrCH_2Cl$	1011	Hand
Dibromodifluoromethane	Br_2CF_2	1202	Fixed a/
Bromochlorodifluoromethane	$BrClF_2$	1211	Fixed/Hand b/
Bromotrifluoromethane	$BrCF_3$	1301	Fixed b/, d/
Carbon tetrachloride	CCl_4	104	Hand
Dibromotetrafluoroethane	BrF_2CCBrF_2	2402	Hand c/

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a/ Declining use in the United States Air Force applications.

b/ Recognized by NFPA Standards.

c/ Limited use in Italy and Russia, no U.S. use.

d/ Halon-1301 is also mixed with Halon-1211 in small hand-held extinguishers.

Halon-1301 and Halon-1211 have excellent flame extinguishment properties and acceptable toxicity under favorable circumstances. However, there are significant health risks if the fire is not quickly extinguished. Halons undergo pyrolysis when subject to flame or surface temperatures greater than 480°C. The extent of pyrolysis depends on length of exposure to high temperatures, the Halon concentration, and the degree of mixing. Halon-1301 decomposition products are halogen acids, hydrogen fluoride (HF), hydrogen bromide (HBr), the free halogens (Br_2), and small amounts of carbonyl halides (COF_2), $COBr_2$). Halon-1211 has the same decomposition products as Halon-1301 plus hydrogen chloride (HCl), chlorine gas (Cl_2), and phosgene ($COCl_2$) (NFPA 1986).

Halon-1301 and Halon-1211 are the only halogenated extinguishing agents recognized by the National Fire Protection Association (NFPA) for use in the United States. They have a combination of desirable characteristics:

- low toxicity in occupied spaces (in most circumstances);
- low electrical conductivity;
- high visibility during use;
- little corrosive or abrasive residue; and
- high effectiveness per pound of chemical.

In stationary or fixed applications the gaseous Halon-1301 is widely used while the liquid Halon-1211 is preferred in portable applications, where liquid range is desirable.

These chemicals were not used extensively in fire protection until the 1970s. Although these compounds are currently produced in small quantities, they are of major concern to ozone protection because use is growing rapidly and because they are believed to be as much as ten times more potent per pound in depleting stratospheric ozone.

Halon-1301 use has increased rapidly for applications like computer centers and art collections because: (1) it can be discharged in an occupied space without significant risk to occupants; (2) it does not damage chemically sensitive contents of the space; and (3) it is very effective against many types of fires. These advantages reduce the financial consequences of accidental extinguisher discharge and allow faster extinguisher deployment since evacuation need not precede discharge. In contrast, extinguishing agents like carbon dioxide (CO_2) can reduce oxygen so quickly that the occupants of the area may be endangered. The absence of residue not only protects property against damage, but allows quicker return to work spaces.

The future demand for Halon-1211 and Halon-1301 will depend on the need for fire extinguishers with their unique properties. The choice depends on property value, fire and fire fighting consequence, probability of fire, the consumer awareness, and product marketing.

The expected continued growth in the use of computing and other expensive electronic equipment indicates that the use of the Halon-1301 may be expected to grow rapidly. The backlog of property with substantial value such as art, antiques, and business records offers large new markets for Halon use.

Military uses, including routine preemptive releases in situations of high fire danger, could drastically increase use.

Studies that Project Halon Emissions

Analysis by the RAND Corporation experts (Hammitt et al., 1986; Camm et al., 1986; and Quinn et al., 1986) present preliminary estimates of the U.S. and world production of these two compounds (estimates do not include production in East Bloc countries). Current U.S. production of Halon-1301 is estimated at 5.4 million kilograms with historic growth rates of 15 to 30 percent per year and world production is estimated at 10.8 million kilograms (Hammitt et al. 1986).

Hammitt (1986) presented the limited information and simplifying assumptions that were used to build the RAND projections:

- U.S. Halon-1301 production was from industry sources.
- World Halon-1301 production was thought to be about twice U.S. production.
- Halon-1211 production was thought to be about the same as Halon-1301 production.
- Future growth rates were based primarily on electronics expansion, not included was an assessment of all property that could be effectively protected by Halon systems.
- Emissions from Halon-1301 systems are based on:
  - 19% for initial system testing;
  - 1%/year for filling and servicing;
  - 0.1%/year for leaks;
  - 1%/year for false discharge;
  - 1%/year fire discharge; and
  - Recycle of Halon-1301 at 40 year intervals.
- Emissions from Halon-1211 portable extinguishers are assumed to be the same as the emissions from fixed Halon-1301 systems excluding recovery.

Exhibit 3-29 presents a range of global Halon projections from Quinn (1986). Three cases are shown for Halon-1301. The Base Case (which uses the assumptions described above) shows considerable near-term growth. The rate of growth slows, and there is a decline in production as recovery of Halon-1301 from retiring systems is used to meet growing demand. Because the average size of new units is also assumed to decline, the net result is a temporary drop in production. Following the decline, production in the Base Case resumes its growth.

Two alternative Halon-1301 cases are also shown in the exhibit. If recovery is assumed not to take place, production grows more rapidly following the year 2000, and there is no decline. If new systems are assumed to decline

EXHIBIT 3-29

Global Halon Projections from Quinn (1986)
(millions of kilograms)

Halon-1301

	Base Case		Without Recovery		Low Charge	
Year	**Use**	**Emissions**	**Use**	**Emissions**	**Use**	**Emissions**
1985	11	3	11	3	7	2
2000	28	9	28	9	12	4
2025	25	15	33	23	7	6
2050	38	22	50	35	13	8
2075	53	33	73	54	19	12

Halon-1211

	Low Use		High Use	
Year	**Use**	**Emissions**	**Use**	**Emissions**
1985	2	1	11	3
2000	6	2	28	9
2025	7	5	33	23
2050	10	7	50	35
2075	15	11	73	54

Source: Quinn et al. (1986)

in size more rapidly than assumed in the Base Case (the Low Charge Case), then use grows more slowly.

Quinn's Halon-1211 scenarios are based on scant information (Quinn 1986, p. 85). The two cases shown in Exhibit 3-29 are based on the assumption that Halon-1211 use is 20 percent of (Low Case) or equal to (High Case) the Halon-1301 Base Case projection. For both of the Halon-1211 cases shown, it is assumed that no recovery is undertaken.

Hammitt et al. (1986) and Camm et al. (1986) built upon Quinn's work to develop a range of production projections for the Halons. The uncertainty analysis used to develop these projections is described above in the section on CFC scenarios. Exhibit 3-30 presents the full range of projections presented by the authors. A range of scenarios is presented based on subjective quantile estimates. Because the uncertainty ranges are subjective, it is not possible to associate the low or high values with specific events such as no recovery or low charge. Of note is that these projections assume that Halon-1211 production is comparable to Halon-1301 production, and not 20 percent of the value as potentially indicated by Quinn.

Although the RAND effort is a contribution to our understanding of the potential significance of Halons to stratospheric ozone depletion, there are reasons to believe that the estimates presented below understate the emissions, perhaps by substantial amounts.

For Halon-1301 systems RAND assumes a 1 percent per year accidental discharge and a 1 percent per year fire discharge. No basis is given for these estimates in the RAND Study. If the actual accidental release was as much as ten times higher and the probability of a fire in a Halon protected space ten times lower (one in a thousand or less), the actual total emissions would increase by more than three hundred percent over those estimated by RAND. In addition, RAND assumed that the volume of Halon protected space would decrease as a result of computer downsizing. RAND made no adjustment for the possibility that other nations will rapidly computerize, thus accelerating the world rate of growth in Halon systems.

Other factors not included in these estimates could lead to even higher releases. For example, the National Fire Protection Association (NFPA) Halon-1301 technical committee has proposed that all new systems be tested with a full-scale release of Halon-1301. This would increase emissions of Halon-1301 by over four hundred percent.

RAND assumed that Halon-1211 use for portable fire extinguishers is about the same as use of Halon-1301 in fixed systems and that it will grow at a similar rate. The product uses are quite different. Halon-1211 is used primarily in hand-held fire extinguishers and U.S. Air Force rapid intervention crash trucks (Hammitt et al. 1986, p. 68). The sizes of these devices reportedly range from 14 ounces to 150 pounds (Quinn et al. 1986, p. 86). Because the devices are small, it is unlikely that significant quantities will be recovered from disposed or deactivated systems. Portable Halon-1211 units are not subject to the same testing by discharge. However, Halon-1211 units are now being marketed as relatively low-cost consumer products. Their superior performance in particular circumstances means that

EXHIBIT 3-30

Hammitt and Camm Global Halon Projections (millions of kilograms)

	Quantile				
	0.05	0.25	0.50	0.75	0.95
Halon-1301					
1985	11	11	11	11	11
2000	11	16	20	26	37
2040	7	21	44	92	259
Halon-1211					
1985	11	11	11	11	11
2000	11	16	20	26	37
2040	8	25	53	111	315

they may face rapid growth, particularly if they are specified for commercial buildings and other business applications or if they are aggressively marketed. Furthermore, it is unlikely that the average useful life of hand-held extinguishers will be as long as 40 years as assumed by RAND.

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A-1

APPENDIX A

CHEMICAL USE ESTIMATES MADE AVAILABLE SINCE PUBLICATION OF THE RISK DRAFT ASSESSMENT[1]

Since the publication of the October 1986 Draft of this Risk Assessment, several new estimates have been made concerning global production and use of CFCs, Chlorocarbons, and Halons. Some of these estimates are revisions to previously published estimates. These new data are discussed below:

World

- Nordhous and Yohe (1986) present revised estimates of U.S., Rest of the World, and Global CFC-11 and CFC-12 production. Projected estimates for nonaerosol applications and the annual growth rates implied by these projections are presented in Exhibit A-1.

  Short term mean global growth rates for CFC-11 and CFC-12 are approximately the same, 3.8 and 3.6 percent respectively. Long term rates are also similar (3.7 percent). Projected U.S. growth for the mean is slower than the global average. In 2050 mean global estimates for CFC-11 and CFC-12 are about five times larger than the 25th percentile estimates. Global estimates in 2050 for the 75th percentile are approximately 20 and 50 percent higher than mean estimates for CFC-11 and CFC-12 respectively.

  In the U.S., the mean estimates for 2050 are equal to (CFC-11) or greater than (CFC-12) the 75th percentile estimates. This result indicates that a skewed distribution of outcomes is expected, with the mean values exceeding the median value (i.e., 50th percentiles) by substantial amounts.

- IEc (1987) estimated U.S. and global Halon-1301 and Halon-1211 use and emissions for fire extinguishing applications through the year 2050.[2] This report estimated historical U.S. use based on industry sources and published reports (Camm and Hammitt 1986; Quinn 1986). IEc developed a computational model that projects Halon stocks and emissions based on release rates, equipment life, and system testing parameters constructed from industry sources. Projections of Halon-1301 were based on projections of the growth of total flooding fire extinguishing systems. Halon-1211 projections were based on the growth of portable fire extinguisher use. IEc (1987) presented nine Halon-1301 and six Halon-1211 projections for the U.S. that alter chemical demand and control technology assumptions. Global estimates are presented for only one baseline scenario. After the publication of this report, IEc revised some of their assumptions for the U.S. and provided projections for "Rest of World" Halon use and emissions to provide a "Best Guess" scenario. This scenario is the only one considered in this summary.

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[1] These results are not used in the RISK ASSESSMENT; they are presented for informational purposes only.

[2] IEc projects "sales" in millions of kilograms. Sales are defined as new production adjusted for imports and exports.

The assumptions used by IEc to project Halon use and emissions are presented in Exhibit A-2. "Initial Charge Emissions" occur during the construction and activation of fire extinguishing units or systems. "Bank Emissions" occur annually from stored chemical in existing systems. "Recovery at Disposal" indicates the percent of chemical that is reused and not emitted from a retiring system. Systems charged with Halon-1301 emit a larger percentage of their initial change when compared to units using Halon-1211. However, disposal recovery rates were greater for Halon-1301 systems.

Exhibit A-3 shows projected U.S. and global Halon use and the implied growth rates over time for the IEc "Best Guess" scenario. Halon-1301 use in the U.S. is projected to be flat until 2000 and then grow approximately three percent annually until 2050. Global use is projected to grow slowly in the short term and then accelerate after 2000. Halon-1211 use for the U.S. and the world is expected to grow rapidly in the short term (5.7 and 8.8 percent respectively) and then slow to rates similar to long term growth for Halon-1301 (about 3 percent annually). Growth rates for emissions are significantly higher than sales for both compounds because of the slow release rates of Halons from fire extinguisher applications.

IEc projections differ significantly from previously published estimates in Camm and Hammitt (1986) and Quinn (1986). Exhibit A-4 shows the short and long term growth rates for these reports and IEc (1987). IEc short term projections for Halon-1301 are lower than almost all other previous projections. Short term projections for Halon-1211 are higher than all previous short term projections. IEc long term projections for both Halon-1301 and Halon-1211 are higher than the "Middle" estimates for Camm and Hammitt (1986).

United States

- ITC (1987) provides revised 1985 U.S. production estimates of 79.7 and 136.9 million kilograms for CFC-11 and CFC-12, respectively. This publication also presented preliminary 1986 estimates of 91.3 and 146.2 million kilograms for CFC-11 and CFC-12. The implied growth of combined production from 1985 to 1986 is 9.6 percent.

EEC

- EFCTC (1986) estimates 1985 EEC use of CFC-11, CFC-12, and combined CFC-113 and CFC-114. Use is reported as 135.9, 92.6 and 43.7 million kilograms for these compounds, respectively. For combined CFC-11 and CFC-12 use, this reflects a 5.0 percent growth from 1984 to 1985. CFC-113/CFC-114 growth is 13.3 percent for the same time period.

Japan

- Araki (1986) estimates 1986 CFC-113 production in Japan as 51.5 million kilograms.

USSR

- o Tirpak (1986) summarizes the results of the Global Climate Change Work Group VIII's conference in the USSR. In these meetings Soviet sources reported 1986 USSR CFC-11 and CFC-12 production of 103.0 million kilograms. In addition, these sources indicated that annual production capacity would increase for CFC-11 and CFC-12 to 140 million kilograms by 1990. Assuming production capacity is fully utilized, this implies an 8.0 percent annual increase in production of CFC-11 and CFC-12 through 1990.

Canada

- o Buxton (1987) estimates total 1986 Canadian CFC production as 20 million kilograms.

Other

- o Dupont (1987) estimates per capita CFC consumption for 72 countries. This source divides these countries into four groups:

  -- less than 0.1 kilograms per capita;

  -- 0.1 to 0.2 kilograms per capita;

  -- 0.2 to 0.5 kilograms per capita; and

  -- greater than 0.5 kilograms per capita.

  A range of estimated use for each country is calculated by multiplying 1985 population by estimated use per capita for each country. These use estimates are presented in Exhibit A-5.

EXHIBIT A-1

GLOBAL ANNUAL PRODUCTION IN MILLIONS OF KILOGRAMS
(Annual Average Growth Rate in Percent)

	25th Percentile	75th Percentile	Mean
Non-Aerosol CFC-11			
1980	193.3 (1.8)	193.3 (4.9)	193.3 (3.8)
2000	275.0 (1.0)	506.5 (3.7)	405.2 (3.7)
2050	446.5	3,045.6	2,470.3
Non-Aerosol CFC-12			
1980	249.1 (1.6)	249.1 (4.9)	249.1 (3.6)
2000	345.5 (1.1)	651.2 (4.1)	503.1 (3.7)
2050	600.3	4,802.2	3,071.7

U.S. ANNUAL PRODUCTION IN MILLIONS OF KILOGRAMS[a]
(Annual Average Growth Rate in Percent)

	25th Percentile	75th Percentile	Mean
Non-Aerosol CFC-11			
1980	67.6 (1.4)	67.6 (4.1)	67.6 (3.2)
2000	89.4 (0.0)	151.8 (2.3)	127.3 (2.6)
2050	90.3	471.0	470.2
Non-Aerosol CFC-12			
1980	128.3 (1.1)	128.3 (4.4)	128.3 (3.2)
2000	160.5 (0.3)	301.6 (2.4)	239.7 (3.0)
2050	190.3	983.9	1,030.9

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a/ Non-aerosol compound growth accounts for essentially all growth in the U.S.

SOURCE: Nordhaus and Yohe (1986).

EXHIBIT A-2

ASSUMPTIONS FOR IEc HALON PROJECTIONS

	Halon-1301		Halon-1211	
	U.S.	Rest of World	U.S.	Rest of World
Initial Charge Emissions				
Manufacturing/Installation Discharges:	3.7%	3.7%	1.6%	1.6%
New Filling Related Discharges:	3.8%	3.8%	d/	d/
Discharge Testing:	12.6%-5.0% a/	12.6%	1.4%-5.0% a/	1.4%
Bank Emissions				
Service Discharges:	0.6%-0.3% /year a/	0.6% /year	d/	d/
Unwanted Discharge:	1.3%-1.2% /year a/	1.3% /year	0.4%-0.3% /year a/	0.4% /year
Training Discharges:	0.3% /year	0.3% /year	1.0% /year	2.6% /year
Fire Discharges:	1.5% /year	1.5% /year	1.3% /year	1.3% /year
Percent of Fire Discharges Destroyed:	1.0% /year	1.0% /year	10.0% /year	10.0% /year
Recovery at Disposal:	67.5%-85.5% b/	67.5%	15.0%-52.0% c/	15.0%
Other Assumptions				
Assumed System Life:	25 yrs	25 yrs	20 yrs	20 yrs

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a/ This range reflects the change in assumptions from 1985 to 1990. The value on the right of the range is used after 1990.

b/ This range reflects the change in assumptions from 1985 to 1992. The value on the right of the range is used after 1992.

c/ This range reflects the change in assumptions from 1985 to 1995. The value on the right of the range is used after 1995.

d/ IEc does not estimate these categories.

SOURCE: IEc (1987).

EXHIBIT A-3

IEC PROJECTIONS OF SALES AND EMISSIONS FOR HALON-1301 AND HALON-1211

	IEC Halon-1301 Estimates					IEC Halon-1211 Estimates			
	USA Total Use Halon-1301 (Mill KG)	USA Emissions Halon-1301 (Mill KG)	World Total Use Halon-1301 (Mill KG)	World Emissions Halon-1301 (Mill KG)		USA Total Use Halon-1211 (Mill KG)	USA Emissions Halon-1211 (Mill KG)	World Total Use Halon-1211 (Mill KG)	World Emissions Halon-1211 (Mill KG)
1965	0.0	0.0	0.0	0.0	1965	0.0	0.0	0.0	0.0
1970	0.1	0.0	0.2	0.0	1970	0.1	0.0	0.2	0.0
1975	0.6	0.1	1.2	0.2	1975	0.3	0.0	1.2	0.1
1980	1.8	0.3	3.6	0.6	1980	0.9	0.1	3.6	0.6
1985	3.5	1.0	7.0	2.0	1985	2.8	0.4	7.0	1.5
1990	4.6	1.4	9.5	3.1	1990	4.1	0.8	14.6	3.3
1995	4.6	1.8	9.7	4.0	1995	5.5	1.4	20.3	6.4
2000	3.9	2.1	8.2	4.7	2000	6.4	2.2	24.7	10.5
2005	4.7	2.7	10.2	6.2	2005	7.2	3.5	27.1	14.5
2010	5.7	3.3	12.5	7.8	2010	7.5	4.4	31.6	21.3
2015	6.7	4.0	14.7	9.3	2015	8.9	5.4	37.9	26.0
2020	7.5	4.4	16.4	10.2	2020	10.3	6.2	43.8	30.0
2025	8.4	4.8	18.1	10.8	2025	12.1	7.3	49.1	33.0
2030	10.0	5.8	21.7	13.3	2030	13.7	8.1	57.7	39.1
2035	11.8	6.9	25.8	16.0	2035	16.1	9.7	68.1	46.6
2040	13.7	8.1	30.2	18.8	2040	18.6	11.1	78.8	53.8
2045	15.7	9.1	34.3	21.2	2045	21.7	13.1	89.6	60.6
2050	17.9	10.3	38.9	23.6	2050	24.8	14.8	104.7	71.1

Growth Rates for Sales and Emissions for Halon-1301 and Halon-1211
(Percent)

	Halon-1301					Halon-1211			
1985-2000	0.7	5.0	1.1	5.9	1985-2000	5.7	12.0	8.8	13.9
2000-2050	3.1	3.2	3.2	3.3	2000-2050	2.7	3.9	2.9	3.9
1985-2050	2.5	3.6	2.7	3.9	1985-2050	3.4	5.7	4.2	6.1

EXHIBIT A-4

GLOBAL HALON-1301 AND HALON-1211 GROWTH RATES
(Percent)

Short Term Growth: 1985-2000

Halon-1301	IEc (1987)	Camm and Hammitt (1986) a/	Quinn (1986) b/
Lower Bound	--	0.0	--
Low Bound	--	2.5	3.6
Middle	1.1	4.1	6.4
High Bound	--	5.9	6.4
Higher Bound	--	8.4	--
Halon-1211			
Lower Bound	--	0.0	--
Low Bound	--	2.5	7.6
Middle	8.8	4.1	--
High Bound	--	5.9	6.4
Higher Bound	--	8.4	--

Long Term Growth: After 2000

Halon-1301	IEc (1987) c/	Camm and Hammitt (1986) c/	Quinn (1986) d/
Lower Bound	--	-1.1	--
Low Bound	--	0.6	0.9
Middle	3.2	2.0	1.3
High Bound	--	3.2	2.0
Higher Bound	--	5.0	--
Halon-1211			
Lower Bound	--	-0.8	--
Low Bound	--	1.1	1.0
Middle	2.9	2.5	--
High Bound	--	3.7	1.2
Higher Bound	--	5.5	--

a/ Estimates represent 5th, 25th, 50th, 75th, and 95th percentiles.

b/ Estimates represent Low Charge (Low Bound), Base Case (Middle), and Without Recovery (High Bound) scenarios for Halon 1301. Halon 1211 estimates represent Low and High Use scenario. Note Halon 1211 growth rates for the Low Bound exceed rates in the High Bound case even though absolute production is much lower .

c/ Projections are from 2000 to 2050.

d/ Quinn projections for the long term are from 2000 to 2040.

SOURCE: IEc (1987); Camm and Hammitt (1986); and Quinn (1986).

EXHIBIT A-5
DUPONT ESTIMATES OF CFC PER CAPITA USE

Country	1985 Population a/ (thousands)	Range of Implied Country Use (thousands of metric tons)
(Countries with <0.1 kg/cap consumption)		
Belize	0.2 b/	<0.02
Bolivia	6.4	<0.64
Brazil	135.6	<13.56 c/
Chile	12.1	<1.21
Colombia	28.4	<2.84
Costa Rica	2.6	<0.26
Dominican Republic	6.4	<0.64
Ecuador	9.4	<0.94
Egypt	48.5	<4.85
El Salvador	4.8	<0.48
Fiji	0.7 b/	<0.07
Gabon	0.8 b/	<0.08
Guatemala	8.0	<0.08
Honduras	4.4	<0.44
India	765.1	<76.51 c/
Indonesia	162.2	<16.22 c/
Iran	44.6	<4.46
Iraq	15.9	<1.59
Ivory Coast	10.1	<1.01
Kenya	20.4	<2.04
Morocco	21.9	<2.19
Nicaragua	3.3	<0.33
Paraguay	3.7	<0.37
Peoples Republic of China	1,040.3	<104.03 c/
Peru	18.6	<1.86
Philippines	54.7	<5.47 c/
Senegal	6.6	<0.66
Thailand	51.7	<5.17 c/
Togo	3.0	<0.30
Uruguay	3.0	<0.30
Zimbabwe	8.4	<0.84
(Countries with 0.1 to 0.2 kg/cap consumption)		
Algeria	21.9	2.19-4.38
Argentina	30.5	3.05-6.10
Liberia	2.2	0.22-0.44
Malaysia	15.6	1.56-3.12
Mexico	78.8	7.88-15.76
Panama	2.2	0.22-0.44
South Korea	41.1	4.11-8.22
Taiwan	19.1	1.91-3.82
Tunisia	7.1	0.71-1.42
Turkey	50.2	5.02-10.04
U.S.S.R.	277.4	27.74-55.48

EXHIBIT A-5 (Continued)
DUPONT ESTIMATES OF CFC PER CAPITA USE

Country	1985 Population a/ (thousands)	Range of Implied Country Use (thousands of metric tons)
(Countries with 0.2 to 0.5 kg/cap consumption)		
Bahrain	0.4 b/	0.08-0.20
Norway	4.2	0.84-2.10
Portugal	10.2	2.04-5.10
Puerto Rico	3.3 b/	0.66-1.65
Saudi Arabia	11.5	2.30-5.75
South Africa	32.4	6.48-16.20
Spain	38.6	7.72-19.30
Sweden	8.4	0.84-4.20
Venezuela	17.3	3.46-8.65
Yugoslavia	23.1	4.62-11.55
(Countries with >0.5 kg/cap)		
Australia	15.8	>7.90
Austria	7.6	>3.80
Belgium	9.9	>4.45
Canada	25.4	>12.20 d/
Denmark	5.1	>2.55
Ireland	3.6	>1.80
Finland	4.9	>2.45
France	55.2	>27.60 d/
Greece	9.9	>4.45
Israel	4.2	>2.10
Italy	57.1	>28.55
Kuwait	1.7	>0.85
Netherlands	14.5	>7.25
Singapore	2.6	>1.30
Switzerland	6.5	>3.25
U.A.E.	1.4	>0.70
United Kingdom	56.5	>28.25 d/
United States	239.3	>119.65 d/
West Germany	61.0	>30.50 d/

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a/ Most population estimates from (excepted indicated by b/) The World Bank (1987), The World Development Report 1987, Oxford University Press.

b/ 1984 population estimated from The World Bank (1986), The World Bank Atlas, The World Bank Press.

c/ Developing countries with large population may have much less use than this benchmark estimate suggests.

d/ Some developed countries may have much more use than this benchmark estimate suggests.

SOURCE: Dupont (1982).

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CHAPTER 4

FUTURE EMISSIONS AND CONCENTRATIONS OF TRACE GASES WITH PARTLY BIOGENIC SOURCES

SUMMARY

Assessment of the risks of stratospheric modification must be based on realistic projections of atmospheric change. Because the stratosphere can be perturbed by many gases simultaneously, models that attempt to simulate such changes require projections of future concentrations of all relevant trace gases, including those that are wholly industrially produced and those that are partly biogenic.

This chapter summarizes evidence, gathered by a variety of researchers, on past emissions and possible future changes in the concentrations of three gases: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) -- all potentially important stratospheric perturbants. Future concentrations of these gases, particularly methane, are difficult to project for several reasons: current emission sources are not well understood; estimates of the growth in activities that produce emissions depend on future economic, political, and physical forces; future emissions for different activities or natural systems may change as the environment changes; and our understanding of the biogeochemical cycles that control the fate of emissions both now and in the future is incomplete. Together these difficulties make precise projection of future concentrations of trace gases impossible.

Despite these uncertainties, however, atmospheric modelers have generally settled on a narrow range of standard scenarios. While recommending the use of a scenario consistent with prior decisions of the "atmospheric" community in this risk assessment, this chapter also suggests additional sensitivity scenarios useful for examining the range of possible futures of these gases.

The standard scenario adopted is as follows: for CO_2, the 50th percentile scenario prepared for the National Academy of Sciences is recommended (doubling of pre-industrial CO_2 concentrations in 2065); for CH_4, a 0.017 parts per million (ppm) increase per year, the average growth per year based on historic changes, is suggested; for N_2O, a scenario of continued growth in concentrations of 0.2 percent per year is proposed.

Additional sensitivity scenarios are suggested which will improve our understanding of the range of risks that we face. It should be noted that the "standard scenarios" do not reflect the possibility that governments may attempt to limit "greenhouse warming" by controlling the concentrations of these gases (CO_2, CH_4, or N_2O). The assumption that has been implicitly made by extrapolating past rates of growth of these trace gases indefinitely into the future is that future decision makers will never decide to limit global warming (e.g., regardless of the amount the earth warms, greenhouse gases will be allowed to grow). In Chapter 18, the implications of alternative assumptions are analyzed.

FINDINGS

1. FUTURE CONCENTRATIONS OF STRATOSPHERIC PERTURBANTS THAT HAVE AT LEAST SOME BIOGENIC SOURCES, CARBON DIOXIDE, METHANE, AND NITROUS OXIDE, ARE DIFFICULT TO PROJECT (chapter 4).

   1a. The size of existing source terms (wetland areas, for example) is not known with certainty today for all these trace species. Greatest uncertainty exists for methane, least for CO2. To estimate future emissions reliably requires estimating the growth of source terms (e.g., acreage of rice paddies, wetlands area), which will be determined by many technical, political, environmental, and social factors.

   1b. Current emission factors for each source term must be estimated; some are not known today or have not been reliably estimated (emissions from soils, for example).

   1c. Possible changes in emission factors due to changes in the environment must be projected. Projection of changes is difficult because the underlying physical or biological processes that determine emissions are not well understood and because changes in the environment that could alter emissions are not easy to project.

   1d. Biogeochemical cycles that control the fate of emissions once released into the atmosphere must be understood to determine future concentrations of these trace species; severe limitations to our current understanding of these cycles limits our capacity to determine the consequences of changing emissions in the future.

   1e. Possible changes in these biogeochemical cycles due to changes in the environment must be projected; again deficiencies in existing knowledge makes this task difficult.

2. DESPITE THE UNCERTAINTIES ASSOCIATED WITH EACH OF THESE FACTORS, RESEARCHERS HAVE DEVELOPED SCENARIOS FOR THREE GASES WHICH ARE COMMONLY USED. IN THIS RISK ASSESSMENT A SCENARIO CONSISTENT WITH ONES USED IN THE ATMOSPHERIC COMMUNITY'S WILL BE ADOPTED, AS WELL AS SEVERAL SENSITIVITY SCENARIOS TO EXAMINE THE SENSITIVITY OF ATMOSPHERIC EVOLUTION TO THE SCENARIOS (chapter 4).

   2a. The scenarios used in this risk assessment are consistent with that commonly used by the atmospheric community and assume the following changes in trace gas concentrations:

   - for CO2, a scenario developed by the National Academy of Sciences (its 50th percentile, i.e., pre-industrial CO2 concentrations doubling by about 2065);
   - for CH4, a linear increase in concentrations of 0.017 ppm per year;
   - for N2O, concentration increases of 0.2 percent per year.

2b. Additional scenarios used to analyze risks will include:

- for CO2

- o NAS 25th percentile (pre-industrial concentrations doubling by 2100)
- o NAS 75th percentile (pre-industrial concentrations doubling by 2050)

- for CH4

- o 0.01275 ppm per year growth in concentrations (75 percent of the historically observed 0.017 ppm per year increase)
- o 0.02125 ppm per year growth in concentrations (125 percent of the historically observed 0.017 ppm per year increase)
- o 1 percent compound growth per year in concentrations
- o 1 percent compound growth per year in concentrations from 1985 to 2010, followed by constant concentrations at 2.23 ppm
- o 1 percent compound growth per year in concentrations from 1985 to 2020, growing to 1.5 percent compound annual growth by 2050 and thereafter

- for N2O

- o 0.15 percent per year compound growth in concentrations
- o 0.25 percent per year compound growth in concentrations

3. DECISION MAKERS SHOULD BE MADE AWARE THAT THE MOST COMMONLY USED SCENARIOS IN STRATOSPHERIC MODELING IMPLICITLY ASSUME THAT FUTURE DECISION MAKERS NEVER TAKE ACTION TO LIMIT THE RISE IN CONCENTRATIONS OF CARBON DIOXIDE, METHANE, AND NITROUS OXIDE, THREE GASES CONTRIBUTING TO THE GREENHOUSE WARMING (chapter 4).

3a. The standard assumption in most atmospheric modeling has been, by default, that greenhouse gases will be allowed to increase without limit regardless of the level of global warming that occurs or is projected.

3b. In order to provide decision makers with adequate information to assess the risks of ozone modification due to rising CFCs and Halons, alternative assumptions about the future of greenhouse gases need to be examined. Two scenarios are examined:

-- limiting global warming to 2°C.
-- limiting global warming to 3°C.

THE INFLUENCE OF TRACE GASES ON THE STRATOSPHERE AND TROPOSPHERE

Rising concentrations of CO2, CH4, and N2O may influence a number of natural atmospheric and environmental processes (see Exhibit 4-1). Increases in CO2 concentrations have three major effects: (1) CO2 is an important greenhouse gas (Ramanathan et al. 1985); (2) CO2 affects the physiological development of plants, enhancing photosynthesis, decreasing gas exchange and transpiration (water loss), and altering the morphological and biochemical development of plants (Strain and Cure 1985); and (3) CO2, by cooling the stratosphere, increases ozone abundance there (World Meteorological Organization 1986).

CH4 concentrations have two important effects on the stratosphere: (1) CH4 decreases column ozone destruction at lower altitudes; (2) CH4 adds water vapor to the stratosphere, which amplifies global warming and climate change. In the troposphere, CH4 will increase tropospheric ozone, resulting in a further enhancement of the greenhouse effect and possibly an increase in oxidants that affect surface processes (World Meteorological Organization 1986). Carbon monoxide (CO) is considered in this chapter because its abundance, in part, controls and is, in part, controlled by the abundance of CH4 (Thompson and Cicerone 1986; Levine, Rinsland, and Tennille 1985). By altering the abundance of OH, which is a sink for CH4, increases of CO will indirectly increase CH4; decreases in CO will have the opposite effect (Levine, Rinsland, and Tennille 1985).

Increasing tropospheric concentrations of N2O are a major source of global warming (Ramanathan et al. 1985). By itself, an increase in stratospheric N2O would also decrease stratospheric ozone abundance. However, in tandem with increasing chlorine, N2O may interfere with chlorine's catalytic cycle. The net effect depends on the exact scenario (Stolarski, personal communication).

The fact that CO2, CH4, and N2O are all gases that contribute to global warming is important. To the extent that global warming becomes a concern, future emissions of these gases may depend on whether governments undertake policies to directly or indirectly alter these atmospheric concentrations. Nations may, for example, undertake policies to limit carbon monoxide emissions in order to lower CH4 concentrations and reduce global warming. Similarly, nations may control emissions in order to prevent the buildup of oxidants in the troposphere. Future policies may play an important role in determining the emissions and concentrations of these gases. As Mintzer and Miller (1986) note, "[if] restraints were imposed on the buildup of CO2, CH4 and N2O in order to control their contribution to global warming, the role of these gases as moderators of potential ozone depletion in high CFC emission scenarios could be severely limited."

TRACE GAS SCENARIOS

The remainder of this chapter reviews scenarios that researchers have developed to describe possible trends in concentrations of CH4, CO2, and N2O. Efforts to measure past and current concentrations were discussed in Chapter 2; here we examine the current understanding of source terms and fluxes for each gas or its precursors and how these might change over time. This review

EXHIBIT 4-1

EXHIBIT 4-1

EFFECTS OF CHANGES IN COMPOSITION OF ATMOSPHERE

RISING LEVELS	EFFECT ON PLANTS	EFFECT ON SURFACE CLIMATE	EFFECT ON TROPOSPHERIC CHEMISTRY	EFFECT ON STRATOSPHERIC COMPOSITION AND STRUCTURE
CO2	Changes physiology; increases photosynthesis; changes water relations (Strain and Cure 1985)	Greenhouse gas (Ramanathan et al. 1985)	No direct effect	Cools stratosphere, increasing ozone level by slowing destruction processes (NAS 1984)
CH4	None	Greenhouse gas (Ramanathan et al. 1985)	Creates ozone (NAS 1984); alters OH abundance (Khalil and Rasmussen 1985a), increases CO abundance (Thompson and Cicerone 1986). Effect is latitudinally dependent, decreasing with distance from equator (Isaksen and Stordal 1986).	o Interferes with catalytic destruction by chlorine, thereby increasing ozone (NAS 1984) o Alters vertical distribution of ozone, increasing greenhouse effect and possibly changing circulation patterns (World Meteorological Organization 1986) o Creates additional greenhouse effect in stratosphere by adding water, adding to tropospheric greenhouse warming normally considered (World Meteorological Organization 1986).
N2O	None	Greenhouse gas (Ramanathan et al. 1985)	No direct effect	Contributes odd nitrogen to stratosphere: -- can, in some cases, interfere with chlorine catalysis of ozone (Stolarski, personal communication) -- by itself, acts as catalyst to ozone destruction (Stolarski, personal communication)
CO	None	Indirectly increases CO2 and O3, two greenhouse gases (World Meteorological Organization 1986).	Alters OH abundance thereby increasing methane abundance (Thompson and Cicerone 1986)	Does not reach stratosphere in significant quantity; indirect

concentrates on the scenarios generally in use in the atmospheric community. However, other scenarios, which will be used in later chapters in analyzing risks of stratospheric change, are described here as well.

Carbon Dioxide (CO2)

Measured Increases in CO2 Concentrations

Chapter 2 summarizes historical changes in the concentrations of CO2: relatively constant concentrations until the onset of the Industrial Revolution, followed by continuous increases (Pearman et al. 1986; Keeling and GMCC/NOAA 1985).

Historical CO2 Emissions

In the century before the beginning of the industrial revolution the natural losses of CO2 roughly balanced natural emissions, leading only to a seasonal cycle visible each year. After 1850 and the onset of the Industrial Revolution, the heavy use of coal and other fossil fuels (and possibly massive deforestation) led to a large increase in CO2 emissions. Rotty and Marland (1984) have analyzed historical records of fossil fuel use and reconstructed the emissions profile shown in Exhibit 4-2. While fossil fuels are the major source of emissions, such activities as forest clearing and deforestation may have redistributed CO2 from biomass sinks to the atmosphere. However, estimates of the amount of CO2 emitted to the atmosphere as a result of deforestation have declined substantially in recent years (Houghton et al. 1983; Brown and Lugo 1981).

The Carbon Cycle: Estimates of the Current Budget

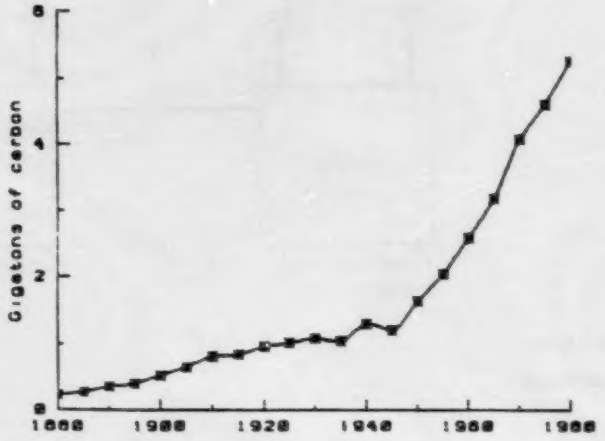
Emissions from fossil fuels are only one part of the biogeochemical processes known as the carbon cycle. Other components of the carbon cycle are the uptake of carbon by the terrestrial biosphere and the uptake, absorption, and outgassing of CO2 in the oceans (Trabalka 1985). Exhibit 4-3 provides a schematic of these components. Understanding the carbon cycle presents an enormous scientific challenge to which much effort has been devoted. The Department of Energy has recently issued a state-of-the-art report Atmospheric Carbon Dioxide and the Global Carbon Cycle, which interested readers should consult for more information (Trabalka 1985). Suffice it to say, even after decades of study there are significant uncertainties in this cycle and disagreement still exists about the size of various sources and sinks and the current fraction airborne.

Projections of Future CO2 Emissions

Future concentrations of CO2 will depend on the quantity of CO2 emissions, the future operation of the carbon cycle, and its impact on the fraction airborne. Consequently, predictions of future CO2 levels are subject to uncertainty. Several researchers have used long-term energy models to represent the socioeconomic factors that contribute to energy use and CO2 emissions. While models differ, in some fashion each model relates world economic production and population growth to energy use and economic efficiency. By making different assumptions about future population and economic growth, the

EXHIBIT 4-2

Historical Carbon Dioxide Emissions from Fossil Fuels and Cement

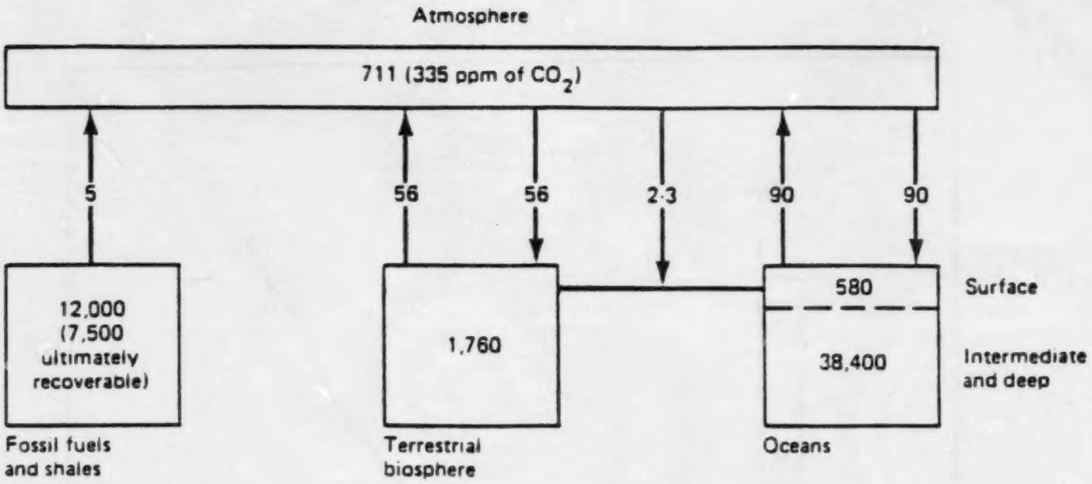


Carbon dioxide emissions have risen rapidly since the outset of the Industrial Revolution.

Source: Rotty and Marland 1984.

EXHIBIT 4-3

A Schematic of the Carbon Cycle


Atmosphere
711 (335 ppm of CO2)
5
56
56
2·3
90
90
12,000 (7,500 ultimately recoverable)
1,760
580
Surface
38,400
Intermediate and deep
Fossil fuels and shales
Terrestrial biosphere
Oceans

Reservoirs in 10^9 metric tons

Fluxes in 10^9 metric tons/year

The stocks of carbon in each natural reservoir and the annual flows that take place among reservoirs are shown. Taken together, these stocks and flows constitute the carbon cycle. Carbon distributed through this cycle plays an important role in the ecological balance of the atmosphere, biosphere, and oceans.

Source: Council on Environmental Quality 1981.

modelers generate projections of future energy use and fuel mix. They then apply average carbon content ratios to compute the associated CO2 emissions (Edmonds and Reilly 1985a).

Perhaps the most widely accepted set of projections was developed for the National Academy of Sciences by Nordhaus and Yohe (1983). In the most likely scenario, CO2 emissions rise from 5 gigatons per year in 1975 to nearly 20 by the year 2100. Other researchers with published projections of CO2 emissions include Seidel and Keyes (1983) and Edmonds et al. (1984). Exhibit 4-4 shows the low, medium, and high projections of each group.

Projections of Future CO2 Concentrations

As future CO2 emissions increase, the fluxes between compartments of the carbon cycle may change. For example, some researchers believe that the ocean's absorption of CO2 may change as the ocean becomes more saturated with CO2 and as ocean circulation patterns are modified. (Emmanuel, Kilbugh, and Olson 1981; Baes, Jr., Bjoerkstroem, and Mulholland 1985.) Photosynthesis may also increase, leading plants to store additional carbon standing biomass, thereby reducing the percentage of CO2 emissions that remains in the atmosphere (Gates, Strain, and Weber 1983). Respiration may increase with warming, altering CO2 emissions from previously inactive storage compartments (Woodwell et al. 1983). Thus, both rising CO2 emissions and an increasing airborne fraction should contribute to future increases in CO2 concentrations.

A widely adopted measure of concentration projections is the "doubling time," the year in which CO2 concentrations reach twice their pre-industrial level. Exhibit 4-4 shows that mid-range projections estimate that a doubling of CO2 could occur as early as 2050 or as late as 2065, assuming a 'well behaved' carbon cycle. If there is, however, a large change in the carbon cycle due to changes in increased or decreased respiration or photosynthesis, these estimates could change.

Standard Scenario Proposed for Assessing Risks and Later Policy Testing

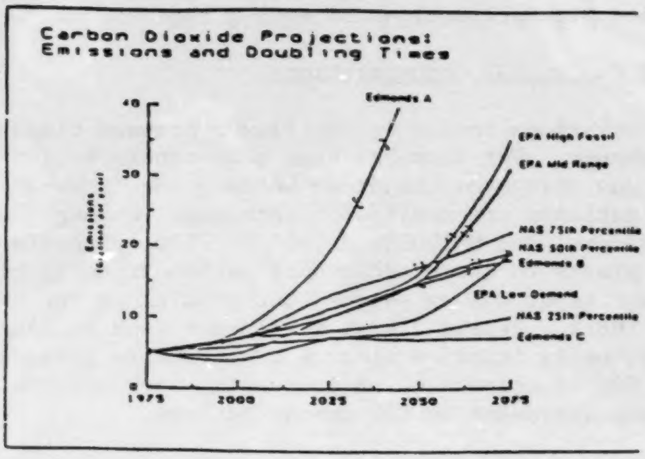
A scenario that will be used for assessing risks of ozone depletion due to increases in CFCs, halons, and other chemicals, will be the NAS 50th Percentile (Nordhaus and Yohe 1983), which is generally consistent with that used in most atmospheric modeling (Ramanathan et al. 1985; Wuebbles, MacCracken, and Luther 1984; World Meteorological Organization 1985). The NAS 50th Percentile Scenario projects the following CO2 concentrations from 1975 to 2100:

	Concentration (ppm)
1975	340
2000	366
2025	422
2050	508
2075	625
2100	770

This scenario assumes that no efforts are made in this period to limit greenhouse warming by limiting CO2.

EXHIBIT 4-4

Projected Carbon Dioxide Emissions and Doubling Time of Concentrations



CO2 emission projections are shown for EPA (Seidel and Keyes 1983), NAS (Nordhaus and Yohe 1983), and Edmonds (Edmonds et al. 1984). The brackets indicate the approximate time at which concentrations reach twice the pre-industrial level.

In addition, the following 25th and 75th percentile scenarios will be examined (these scenarios also assume approximately 50 percent airborne).

	NAS 25th Percentile (ppm)	NAS 75th Percentile (ppm)
1975	340	340
2000	359	380
2025	391	456
2050	434	568
2075	477	735
2100	579	910

Methane (CH4)

Measured Increases in CH4 Concentrations

Chapter 2 summarizes historical changes in CH4 concentrations: relatively constant levels until approximately 150 to 200 years ago, followed by increases that now approximate 0.017 ppm per year (Khalil and Rasmussen 1986).

Historical CH4 Emissions

The extent of scientific agreement on the probable sources and quantities of CH4 emissions (Exhibit 4-5) is quite limited (World Meteorological Organization 1986). In fact, the discrepancies shown in the exhibit probably underestimate uncertainty -- not reflecting, for example, questions emerging about the potential magnitude of tundra as a source of emissions. Our understanding of past changes is limited. Expanded human activities, such as rice cultivation, agriculture, raising cattle, and the use of oil and natural gas, may have increased fluxes from these sources (World Meteorological Organization 1986). Decreases in wetlands may have reduced fluxes from this source. However, because the size of change in each source is uncertain (e.g., rice acreage added), and the flux associated with different conditions for each source is unclear (for example, emissions from different types of rice cultivation vary), we cannot directly estimate past changes in CH4 fluxes through time.

CH4 Photochemistry and Biogeochemical Cycling

Changes in CH4 concentrations depend on changes in CH4 fluxes and the many physical and chemical processes that control the fate of CH4 emissions.

CH4 emitted to the atmosphere (1) combines with the OH radical to form CO2 and water vapor, (2) is reabsorbed by soils and water, and (3) is transported to the stratosphere where it is oxidized to add water vapor and other compounds in that relatively dry region (Thompson and Cicerone 1986).

The key factor controlling the fate of CH4 once it is in the atmosphere is its reaction with OH (Khalil and Rasmussen 1985b). OH concentrations in turn

EXHIBIT 4-5

Estimated CH4 Emission Sources (10^{12} grams per year)

	COLUMN I[a]	COLUMN II[b]
Enteric fermentation (livestock)	100-200	100-150
Rice paddies	~ 280	100 ± 50
Wetlands	190-300	150 ± 50
Biomass burning	--	10 - 60
Freshwater lakes	1-25	--
Oceans	1-17	--
Tundra	0.3-3	--
Anthropogenic/ fossil fuel	16-50	--
Other	--	10-150
TOTAL	586-825	390-765

[a] Column I is taken from Ehhalt (1974) and Ehhalt and Schmidt (1978).

[b] Column II is taken from Khalil and Rasmussen (1983).

Source: World Meteorological Organization (1986).

are determined by CH4, CO, and possibly non-methane hydrocarbons on a localized scale. As such, OH provides a close coupling between CO and CH4: CO concentrations must be considered when interpreting the behavior of CH4 in the atmosphere. One possible cause for a temporal increase in CH4 concentrations is a declining supply of OH brought about by increasing CO (Khalil and Rasmussen 1985b; Levine, Rinsland, and Tennille 1985).

An example of the interaction between CO and CH4 appears in Exhibit 4-6 from Thompson and Cicerone. Note that increases in CO emissions, by decreasing the OH abundance, increase the CH4 lifetime and concentrations; decreasing CO will tend to have the opposite effect. Unfortunately, there are two factors that complicate analysis of actual CO and CH4 trends and predictions of future changes in these trace gases. The first is that atmospheric CO trends are harder to discern than are CH4 trends, although there is accumulating evidence that at least in some locations CO is increasing (see below) (Rinsland and Levine 1985; Khalil and Rasmussen 1983). The second is that measurements of OH are nearly nonexistent and both present-day and historical OH can only be deduced from model calculations. Calculations show that there are numerous factors besides concentrations of CH4 and CO that determine OH concentrations, and hence methane lifetimes (Thompson and Cicerone 1986). These include O3, water vapor distributions, the amount of sunlight and concentrations of soluble OH end-product gases that can be rained out (e.g., HNO3, H2O2). All of these factors vary widely in time and with locality and season. Reactive non-methane hydrocarbons (presumably both those emitted by human activities and those occurring naturally from vegetation) may control OH more effectively than CO and CH4 in areas where their concentrations are high. Ozone and NOx (NOx = NO + NO2) levels are critical to OH concentrations since O3 is the precursor species for OH. For example, at low NOx concentrations, increasing CO and CH4 suppresses OH almost uniformly throughout the troposphere, but at high NOx (as would be found in a continental or urban environment), increasing CH4 or CO contributes to photochemical ozone formation and increases OH near the ground and in the upper troposphere (Hameed, Pinto, and Stewart 1979; Thompson and Cicerone 1985).

Consequently, if one were to estimate future CH4 concentrations from models one would need to estimate not only future CH4 fluxes, but future fluxes of many other gases, as well as a variety of environmental conditions, none of which can be precisely forecast at this time.

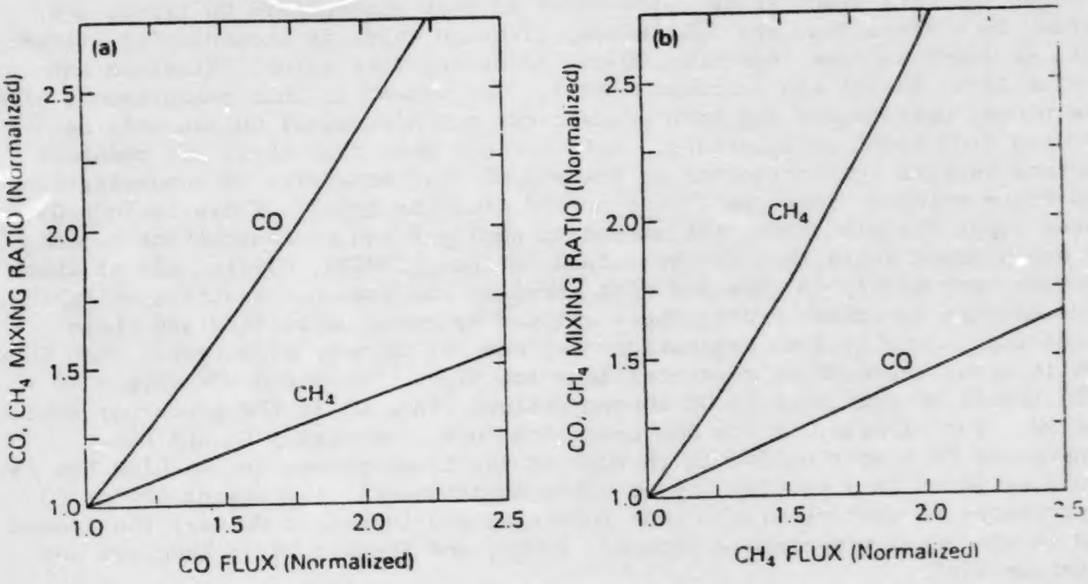
Projections of Future Emissions of Methane

If CH4 emissions are to continue to grow, increases in source terms and/or emission rates would be required. Empirical work on this subject is limited, although certain educated guesses may be possible (Hoffman and Wells 1986) (see Exhibit 4-7).

Consequently, as Exhibit 4-7 outlines, it is possible that CH4 emissions will cease growing (if they are growing now). This could happen if increases in the size of various sources slow (rice acreage, for example), if source terms are eliminated (forests, for example), or if emissions factors decline (from rice paddies, for example, if CO2 reduces transport by changing stomatal resistance). However, it is also possible that increases in temperature or changes in hydrology will increase emissions factors for some sources (from tundra, for example), compensating for, or overwhelming any decreases in source-term quantities (Hoffman and Wells 1986).

EXHIBIT 4-6

Two Ways That CH4 Concentrations Could Have Changed



As a consequence of coupling between CO and CH4, due to their reactions with OH, concentrations of CH4 can increase both through increases in CO fluxes (a) and CH4 fluxes (b).

Source: Thompson and Cicerone 1985.

EXHIBIT 4-7

Possible Changes in CH4 Sources and in Emission Factors

SOURCE TERMS	POSSIBLE CHANGE IN LEVEL OF SOURCE TERMS	POSSIBLE CHANGE IN EMISSION FACTOR FOR SOURCE TERMS
Rice	To slow and then stabilize with population	Decline possible if: o increased CO2 reduces emissions by reducing transport through plants o cultivars shift o cropping practices remove wastes Increases possible if warmer temperatures raise emissions per unit biomass
Livestock	To slow and then stabilize	Possible decrease with biotechnology to reduce methanogenesis and "wasted" energy
Deforestation	To slow, then disappear	--
Wetlands	Loss of wetlands should increase, then slow and stabilize	Possible increase with temperature/decrease with CO2
Mining	Increasing	No information available
Tundra	None	Changes are possible: o Increase with rising temperature if methanogenesis increases o Decrease with rising temperature if several microorganisms are cold-tolerant and subject to adverse selection if warming occurs

Source: Hoffman and Wells 1986

Projections Of other Gases Influencing Future CH4 Concentrations

Future concentrations of CH4 will be influenced by the OH radical and the trace gases such as CO, NOx, and non-methane hydrocarbons that help determine its concentration. In this section, we summarize our current understanding of these gases:

1) Measured Trends in CO Concentrations. Chapter 2 summarizes measurements of atmospheric CO concentrations: annual increases of approximately 1 percent to 2 percent since the 1950s.

2) Current and Historical CO Emissions. Information about past and current CO emissions is sparse. Logan (1985) has made estimates of the current sources and sinks of CO emissions (Exhibit 4-8). Estimates of past global CO emissions have not been made, except by use of models that make assumptions about concentrations of CH4 and CO. Kavanaugh (1986) has recently completed a study of historical CO emissions from combustion. He estimates that from 1960 to 1975, emissions of CO from fossil fuel combustion increased at a rate of 1.7 percent per year.

3) Future Emissions of CO. Estimates of future emissions of CO require projecting changes in all source terms and their associated emission factors. A search of the literature revealed no published literature of future CO emissions from natural sources. Kavanaugh (1986), however, argues that there is likely to be a substantial reduction in future CO emissions from combustion.

Exhibit 4-9 shows three such scenarios. The cause of the expected decline in CO emissions is the penetration of efficient engines into world vehicle markets, the substitution of ethanol, diesel, and unleaded gasoline for leaded gasoline, and the adoption of pollution-reduction equipment in some parts of the world's transportation sector (Kavanaugh 1986).

Furthermore, to the extent that CO emissions stem from forest clearing, this source of emissions can be expected to slow and eventually terminate, as the supply of clearable forest areas becomes exhausted.

4) Past, Current, and Future Emissions of NOx, OH, and Non-Methane Hydrocarbons. NOx and non-methane hydrocarbons, through their effect on OH and CO, play a role in determining CH4 concentrations. Unfortunately, there is little historical information on these compounds and even present-day ambient data are uneven in quality and spatial resolution. An evaluation of past NOx and non-methane hydrocarbon combustion sources is underway (Dignon and Hameed 1986; Hameed, personal communication to Anne Thompson, 1986). These gases are also relevant to the formation of tropospheric ozone, which may be increasing (Logan 1985).

Scenarios for CH4 Proposed for Assessing Risks and Later Policy Testing

Current information about sources, future source size, emission rates and future emission rates has not yet been integrated to develop projections of CH4 concentrations based on modeling from 'the ground up.' In absence of anything better, a reasonable approach to projecting future methane concentrations would be to extrapolate past increases of 0.017 ppm indefinitely into the future. Research should focus on all of the areas discussed earlier in this chapter, including the following: how the CH4 sources would change over time (how much

EXHIBIT 4-8

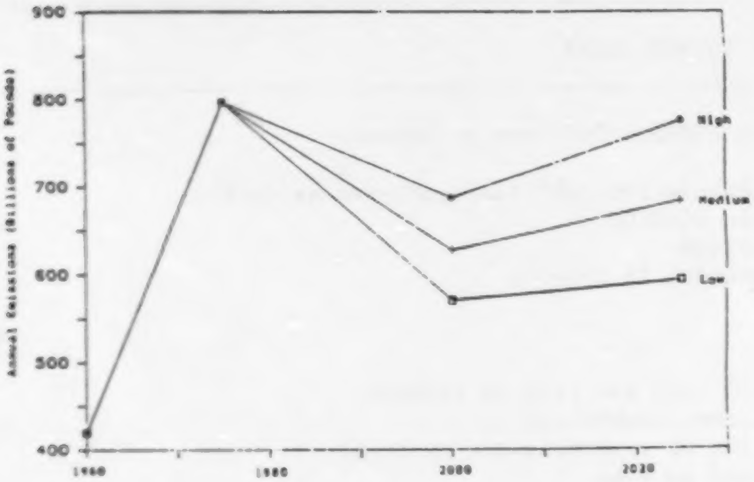
Current Sources and Sinks of Carbon Monoxide (1984 Concentrations of CO: 30-200 ppb)

SOURCE GASES	
Atmospheric burden (10^6 tons as carbon)	200
Sinks + Accumulation (10^6 tons per year as carbon)	
Reaction with OH	820±300
Soil uptake	100
Accumulation (5.5%/yr.)	10
TOTAL	940±330
Sources (10^6 tons per year as carbon)	
Fossil fuel combustion	190
Oxidation of anthropogenic hydrocarbons	40
Wood used as fuel	20
Oceans	20
Oxidation of CH_4	260
Forest wild fires (temperate zone)	10
Agricultural burning (temperate zone)	10
Oxidation of natural hydrocarbons (temperate zone)	100
Burning of savanna and agricultural land (tropics)	100
Forest clearing (tropics)	160
Oxidation of natural hydrocarbons (tropics)	150
TOTAL	1060
Tropical Contribution	
Burning	100
Forest clearing	160
Oxidation of hydrocarbons	150
TOTAL	410

Source: Logan et al. (1981), updated by Logan et al. (private communication, 1984), as reported in World Meteorological Organization (1986).

EXHIBIT 4-9

Scenarios of Carbon Monoxide (CO) Emissions from Combustion



Future carbon monoxide emissions from combustion, as projected by Kavanaugh (1986). The case of the expected decline is the penetration of efficient engines into world markets, the substitution of cleaner fuels, and the increased use of pollution reduction equipment in transportation.

Source: Kavanaugh (1986).

more rice paddies and cattle, how much less wetland area, etc.); how emission rates (e.g., emissions per acre of rice) would change because of alterations in temperature, water, cultivation practices, and atmospheric CO2; how CO, NOx, and non-methane hydrocarbon emissions will change; and how tropospheric chemical balances will change as a result. The time to attempt such an effort is clearly upon us.

Because future methane concentrations are uncertain, the following wide range of sensitivity scenarios of CH4 concentrations are suggested for use in Chapter 18:

- Case 1. CH4 concentrations increase by 0.01275 ppm per year (75 percent of the historically observed 0.017 ppm per year increase).
- Case 2. CH4 concentrations increase by 0.02125 ppm per year (125 percent of the historically observed 0.017 ppm per year increase).
- Case 3. CH4 concentrations increase by 1 percent per year from 1985 to 2010, followed by constant concentrations at 2.23 ppm. This scenario, proposed by Hoffman and Wells (1986), attempts to reflect the slowing or cessation of deforestation, a source of CO and CH4 fluxes.
- Case 4. CH4 concentrations increase by 1 percent per year from 1985 to 2020, followed by a 1.5 percent per year increase after 2050. This scenario, recommended by Hoffman and Wells (1986), asserts that temperature increases overwhelm other forces that would tend to reduce the growth of CO and CH4 fluxes.

These scenarios can help illuminate the effects of uncertainty about CH4 on column ozone abundance.

Nitrous Oxide (N2O)

Measured Increases in N2O Concentrations

Chapter 2 summarizes that historical changes in N2O concentrations have increased approximately 6 ppb over the last 300 years (Pearman et al. 1986). Currently, concentrations are increasing at about 0.2 percent per year (WMO 1986).

Historical N2O Emissions

The major sources of N2O are emissions from soils, fossil fuel combustion, and fertilizer use (McElroy and Wofsy 1984). Researchers estimate that fossil fuel combustion currently accounts for between 20 percent and 30 percent of the emissions, with fertilizers and natural sources contributing the remainder (McElroy and Wofsy 1984). However, the change in global emissions may be mostly attributable to fossil fuel burning.

N2O and the Biogeochemical Cycle

The only known sink for N2O is stratospheric photolysis and reaction with singlet atomic oxygen. Both processes occur only in the upper atmosphere, and the atmospheric residence time of N2O is consequently long -- approximately 100 to 175 years (World Meteorological Organization 1986). As with the CFCs, the long lifetime means that curtailing the growth of N2O emissions so that N2O emissions are held constant would not prevent an increase in N2O concentrations for many decades, since N2O is far from the equilibrium value with its current emissions.

Projections of Future N2O Emissions and Concentrations

Future emissions of N2O will primarily depend on fossil fuel combustion, natural emissions, and agricultural activity. Estimates of future N2O emissions from energy combustion were prepared by Kavanaugh (1986). Kavanaugh used the Institute for Energy Analysis/Oak Ridge Associated Universities Long-Term Global Energy Model to project fossil fuel use (Edmonds and Reilly 1985b). He compiled current emission factors and considered possible changes in emission factors (from increased adoption of catalytic convertors, for example). Kavanaugh found large increases in N2O emissions from combustion: "a doubling in emissions from 1975 to 2000 and a 44% increase from 2000 to 2025." He stated that the "driving force in these changes is rapid economic and population growth in [the rest of the world] and China."

Weiss (1981) developed a simplified atmospheric model that computes atmospheric N2O concentrations from increases in N2O emissions. Input to the Weiss model is the aggregate emissions growth rate in each time period. To compute this aggregate growth rate, emissions from all sources must be projected. Estimates for future changes in the flux of agricultural and natural emissions have not been developed, however.

To conduct a preliminary analysis of future N2O concentrations, we developed simplified scenarios for each source term. The combustion source was assumed to contribute 31 percent of the total (McElroy and Wofsy 1984). Projections of combustion were taken from Kavanaugh (1986). The agricultural source was assumed to contribute 58 percent of the total (McElroy and Wofsy 1984). In the absence of independent projections, it was assumed that the agricultural source would increase at the same rate as world population. The population projections, consistent with those in the energy model, were based on the work of Keyfitz and are discussed in Gibbs (1986). Natural fluxes, assumed to contribute 11 percent of total emissions (McElroy and Wofsy 1984), were held constant.

Using the baseline distribution of source terms and the projected increases in each source, aggregate growth rates were computed. Exhibit 4-10 presents the growth in emissions from each source and the aggregate growth rate.

These increases in N2O emissions were used as inputs to the Weiss (1981) model. Exhibit 4-11 shows that the computed concentrations for this preliminary scenario are consistent with the N2O concentrations scenarios generally used by the atmospheric modeling community.

Standard Scenario Proposed for Assessing Risks and Later Policy Testing

Because our preliminary emission-concentrations analysis gives results consistent with the scenario commonly used by the atmospheric modeling community, we propose using this scenario -- 0.20 percent growth per year -- for the standard case for risk assessment. The standard scenario assumes no effort is made to limit emissions caused by human activity. Sensitivity tests of 0.15 percent and 0.25 percent will also be examined.

EXHIBIT 4-10

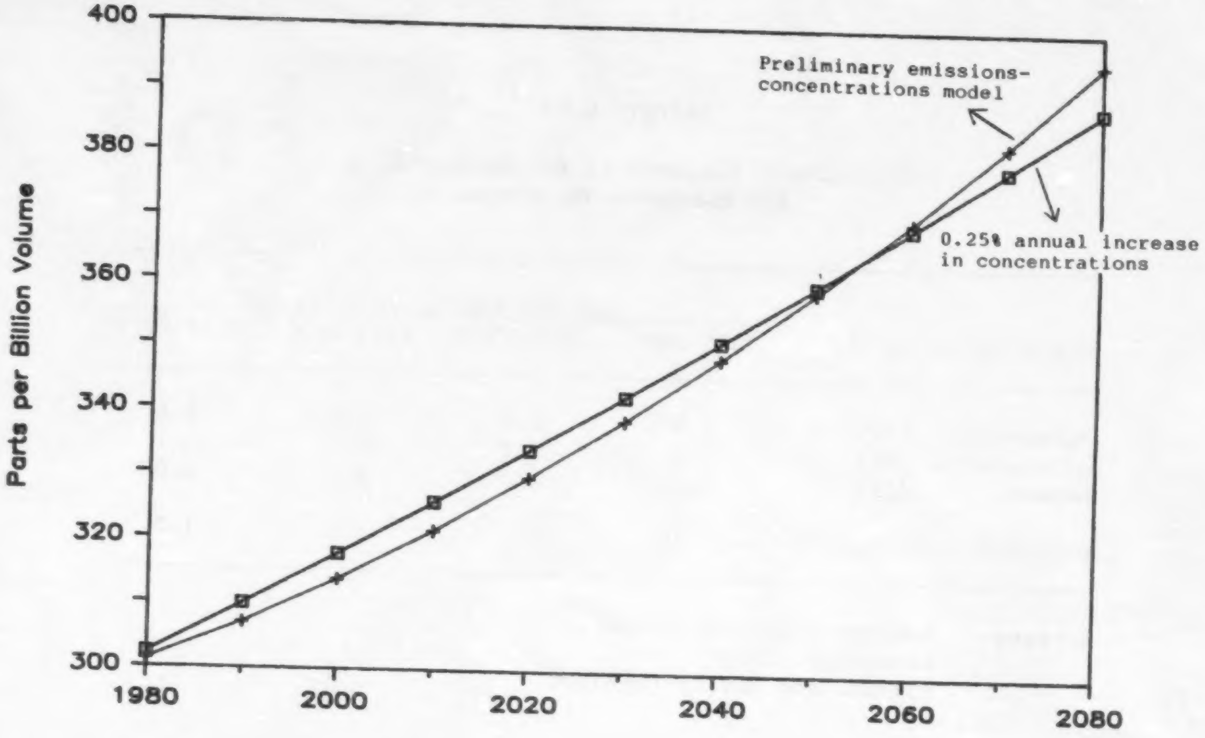
Preliminary Scenario of Future Growth in N2O Emissions by Source

SOURCE (% of total)	PERCENT ANNUAL GROWTH RATE 1975-2000	2000-2025	2025-2050	2050-2075
Combustion (31)	2.9	1.6	1.6	1.6
Agricultural (58)	1.6	0.9	0.4	0.1
Natural (11)	0.0	0.0	0.0	0.0
AGGREGATE (100)	1.9	1.1	1.0	1.0

Sources: McElroy and Wofsy (1984)
Kavanaugh (1986)
Edmonds and Reilly (1985b)

EXHIBIT 4-11

Projected Nitrous Oxide (NO2) Concentrations



EFFECTS OF POSSIBLE FUTURE LIMITS ON GLOBAL WARMING

CO2, CH4, and N2O are radiatively active trace gases that may contribute to future global warming (Ramanathan et al. 1985; Cicerone and Dickinson 1986; Wang, Wuebbles, and Washington 1985). To the extent that decision makers become concerned about global warming, governments may take action to limit the rise in the concentrations of these trace gases.

Mintzer and Miller (1986) suggest that several measures are available to reduce greenhouse gases -- either directly, by limiting their emissions, or indirectly, by manipulating their atmospheric loss terms. To reduce CO2 emissions from biogenic sources, they suggest reforestation efforts. To control CH4 concentrations, they suggest regulations to limit emissions and natural gas pipelines, coal mines, and oil fields. Buildup in the atmosphere, they contend, could also be limited by efforts to reduce CO emissions, which, as this chapter discussed earlier, may deplete OH concentrations, which are a major loss term for CH4. A recent workshop report indicated that N2O might be controlled through better combustion practices (EPA 1986).

It is beyond the scope of this chapter to evaluate the likelihood of successful government action to limit greenhouse gas increases. No one knows how future decision makers will respond to greenhouse warming. The default assumption of the standard scenarios has been that no response will develop. That assumption constitutes one bound of possibility. Another bound might be that major efforts are undertaken to stabilize global atmospheric concentrations. In between these extremes, a range of possibilities exists. In order to provide decision makers with an assessment of the risks of ozone depletion for various emission scenarios of ozone-depleting substances, Chapter 18 will analyze scenarios in which total global warming is limited to 2°C or 3°C (plus or minus 50%, the uncertainty attached to any radiative forcing by the National Academy of Science evaluations on climate change -- see Chapter 6).

CONCLUSION

Because N2O and CO2 are long-lived gases, their concentrations are likely to rise despite significant uncertainties about future emissions trends. Future concentrations of CH4 are another matter, however. CH4 has a relatively short lifetime and the factors that determine its production and loss terms are quite difficult to predict. Its future is more difficult to project reliably.

Exhibit 4-12 presents the combined scenarios proposed for use in risk assessment analysis. In Chapter 18, alternative scenarios are examined, which examines how risks would change if future decision makers decide to limit global warming to 2°C or 3°C.

EXHIBIT 4-12

Summary of Standard Scenarios Proposed for Assessment

Carbon dioxide (CO2) concentrations (ppm)

YEAR	Reference NAS 50th Percentile	Sensitivity Cases NAS 25th Percentile	 NAS 27th Percentile
1975	340	340	340
2000	366	359	380
2025	422	391	456
2050	508	434	568
2075	625	477	735
2100	770	579	910

Source: Nordhaus and Yohe (1983).

Methane (CH4) concentrations (ppmv)

	REFERENCE	SENSITIVITY CASES			
	Case 1	Case 2	Case 3	Case 4	Case 5
1980	1.65	1.65	1.65	1.65	1.65
1990	1.84	1.82	1.86	1.82	1.82
2000	2.01	1.95	2.07	2.28	2.28
2010	2.18	2.07	2.29	2.23	2.23
2020	2.35	2.20	2.50	2.23	2.46
2030	2.52	2.33	2.71	2.23	2.79
2040	2.69	2.46	2.92	2.23	3.16
2050	2.86	2.58	3.14	2.23	3.56
2060	3.03	2.71	3.35	2.23	4.16
2070	3.20	2.84	3.56	2.23	4.83
2080	3.32	2.97	3.77	2.23	5.62
2090	3.54	3.09	3.99	2.23	6.53
2100	3.71	3.22	4.20	2.23	7.58

Nitrous oxide (N2O) concentrations:

Standard	Sensitivity	
0.20% annual increase	0.15% annual increase	0.25% annual increase

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CHAPTER 5

ASSESSMENT OF THE RISK OF OZONE MODIFICATION

SUMMARY

Models project that the average global column of ozone will deplete slightly for a time if emissions of chlorofluorocarbons (CFCs) and other chlorine and bromine bearing compounds grow from current levels even if the greenhouse gases that counter ozone depletion continue to grow at current rates. For latitudes greater than 40°N, column depletion is projected even for scenarios in which the emissions of chlorofluorocarbons and other chlorine- bearing substances are reduced to their 1980 levels and emissions of Halons are eliminated. At 60°N, two-dimensional models project that the depletion for this latter scenario would exceed 3 percent by 2030. Depletion would be larger if emissions of ozone-depleting substances grow.

Some uncertainty exists about the validity of model predictions. Although models do a good job of explaining the distribution and abundance of most chemical species in the atmosphere, discrepancies between model predictions and apparent observations of the current atmosphere lower confidence in model predictions.

Another source of uncertainty is that laboratory measurements provide inexact values for various inputs to the models, such as rate constants or cross sections. Over the past 15 years, better laboratory estimates of rate constants and cross sections have produced several alterations in depletion estimates. In order to understand the likelihood that estimates will change again with new laboratory measurements, formal analyses have been done to determine the sensitivity of model projections of ozone depletion to the currently accepted set of best estimates for such inputs. Based on these analyses, depletion appears likely if concentrations of CFCs grow, although a small possibility exists that no depletion would occur.

Formal uncertainty analyses take into account only some of the factors that could alter model predictions. Existing models may omit processes important to determining the future evolution of the stratosphere. No method exists to quantitatively evaluate the impacts of such potentially missing factors. Clearly, the possibility exists that models have omitted a key process and that their predictions under- or overestimate the depletion levels that would be associated with any scenario of trace gas emissions.

The WMO 1986 assessment of stratospheric ozone concluded that from 1970 to 1980 ground-based and balloon monitoring of ozone in the stratosphere shows depletion roughly predicted by models at high and low stratospheric altitudes, as well as the small increases that would generally be expected in the troposphere. Models have failed, however, to predict the observed rapid springtime depletion of ozone that has occurred over and adjacent to Antarctica.

In addition, recent satellite measurements from Nimbus 7 appear to show a decrease in global ozone greater than that simulated in models or that observed by many ground-based systems. However, significant uncertainty exists about these measurements. The atmospheric science community is intensively reviewing this information about both Antarctica and global trends. Until such reviews are concluded, the implications of these results cannot be determined. Consequently, in this risk assessment, we assume that the Antarctic hole and

global trends have no implications for assessing future global risks and do not bring current model projections into question. Future risk assessments will revisit this issue.

Most model projections, including those presented above, have assumed that the atmospheric growth of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) will go unchecked for the period being examined. Since these gases add ozone to the atmosphere or prevent ozone depletion from occurring, growth in their concentrations counters ozone depletion that CFCs and halons are predicted to cause. Future efforts to limit emissions and concentrations of these gases, which might be taken in order to reduce the greenhouse warming, would make the stratosphere significantly more vulnerable to depletion from CFCs and Halons. Thus, the assessment of column depletion risks associated with CFCs and other depleters depends strongly on the assumptions made about whether future decision makers will act to limit increases in emissions and concentrations of those greenhouse gases in the future.

In conclusion, current knowledge indicates that average global ozone will deplete if chlorine continues to grow at current rates and that depletion over much of the United States will exceed the global average. The risk of depletion is higher if the emissions and concentrations of carbon dioxide, methane, and nitrous oxide are reduced as a result of concern over global warming.

FINDINGS

1. STRATOSPHERIC MODELING PROJECTS THAT THE COMBINED EFFECTS OF A VARIETY OF TRACE GASES (CHLOROFLUOROCARBONS, NITROUS OXIDE, CARBON DIOXIDE, HALONS, AND METHANE) ARE LIKELY TO REDUCE THE COLUMN DENSITY OF OZONE UNLESS EMISSIONS OF OZONE DEPLETERS ARE PREVENTED FROM GROWING.

   1a. Photochemical theory continues to support the conclusion that chlorine, nitrogen, and hydrogen can catalytically destroy ozone in the stratosphere, thus depleting column levels.

   1b. One-dimensional (1-D) models currently predict a 5-9 percent depletion for the equilibrium concentrations of chlorine that would result from constant emission of CFCs at 1977 levels. While useful for intercomparing models, these values cannot be used to assess the risks of depletion in an atmosphere in which other gases are also changing.

   1c. One-dimensional (1-D) models predict average column ozone will decrease if global emissions of CFCs and other ozone depleters continue to rise from current levels, even if concentrations of methane, carbon dioxide, and nitrous oxide continue to grow at past rates. For a 3 percent growth of CFCs, models predict over a 25 percent depletion by 2075 if the other gases continue to grow.

   1d. Two-dimensional models (2-D) used in steady state multi-perturbant studies that include chlorine, methane, and nitrous oxide project depletion higher than global averages at latitudes greater than 40°N, especially in the spring.

   1e. Time-dependent simulations of stratospheric change in which 2-D models are used predict that depletion over 4 percent will occur at some latitudes for all cases of positive growth in CFC emissions. Such models even predict ozone depletion of up to 3 percent at inhabited latitudes for a scenario in which emissions of chlorine-bearing substances are reduced from current to 1980 levels and in which halon emissions are eliminated, but in which the greenhouse gases that counter depletion are allowed to grow at historical rates.

   1f. Time-dependent simulation with one 2-D model, with CFCs growing at 3 percent, methane rising at 1 percent, nitrous oxide at 0.25 percent and carbon dioxide growing at 0.6 percent, projects annual average depletion at 40°N of approximately 1.1 percent by 2000 and 5.2 percent by 2030. At 50°N, depletion is projected to be 1.5 percent by 2000 and 6.5 percent by 2030. At 60°N, depletion is projected to be 2.1 percent by 2000 and 8.1 percent by 2030. Springtime depletion would be higher.

   1g. Time-dependent simulation with one 2-D model, with CFC-11 and -12 emissions rolled back to 1980 levels, CFC-113 capped, other chlorinated emissions and bromine emissions eliminated, methane rising at 1 percent, nitrous oxide at 0.25 percent, and carbon dioxide at 0.6 percent, projects depletion by 2030 of about 0.5 percent at 40°N, 0.7 percent at 50°N, and 1.1 percent at 60°N (these depletion values are from 1985 levels). If carbon dioxide concentrations are prevented from growing from current levels, depletion would be anticipated to be higher.

1h. Time-dependent simulations with two other two-dimensional models show roughly comparable results to those reported here, with a slightly less latitudinal gradient. However, these models also project latitudinal gradients from equatorial to polar and regions.

1i. Because of possible increases in the emissions of bromine molecules (see Chapter 4), Halons present a more important risk for stratospheric depletion than has generally been appreciated.

2. CURRENT THEORY AND MODELS FAIL TO REPRESENT ALL OBSERVATIONAL MEASUREMENTS OF THE ATMOSPHERE AND PROCESSES THAT WILL INFLUENCE STRATOSPHERIC CHANGE IN A COMPLETE AND ACCURATE MANNER.

2a. While accurately reproducing many measurements in the current atmosphere, current models fail to reproduce some measurements; the amount of ozone at 40 kilometers is underestimated, for example.

2b. While including representations of most atmospheric processes, current models fail to include all the processes that influence stratospheric composition and structure in a realistic manner. Transport processes, for example, are represented in a simplified manner that does not encompass all the complications of movement in the real atmosphere.

2c. The inability of models to wholly reproduce measurements of the current atmosphere lowers our confidence in them to predict the future; it is possible that models are over- or under-predicting future depletion.

3. UNCERTAINTY ANALYSES THAT CONSIDER A RANGE OF POSSIBLE VALUES FOR CHEMICAL AND PHYSICAL INPUTS CRITICAL FOR MODEL ESTIMATION OF DEPLETION INDICATE THAT DEPLETION IS LIKELY IF CFCS CONTINUE TO GROW.

3a. Uncertainty analyses conducted with one-dimensional models predict depletion for a variety of CFC levels.

3b. Uncertainty analyses using different sets of kinetics and cross sections have not been tested in two-dimensional models. However, different 2-D models have used different approaches for transporting species. This provides a useful test of the sensitivity of model predictions to the uncertainty of how transport actually works. While differing somewhat in the latitudinal gradients of depletion, the models with different transport both predict depletion that increases with distance from the equator.

3c. Not all uncertainties can be tested in the modeling process. The possibility that missing factors may lead to a greater or lesser depletion than indicated in formal uncertainty analyses cannot be excluded.

4. OZONE MONITORING SHOWS CHANGES IN OZONE ROUGHLY CONSISTENT WITH MODEL PREDICTIONS, WITH TWO EXCEPTIONS.

4a. Measurements by balloons and Umkehr show 3 percent depletion at mid-latitudes in the upper atmosphere, 1.3 percent depletion in the lower stratosphere, and 12 percent increases in the lower troposphere. Uncertainty exists about the accuracy of all these observations. These results, however, are roughly consistent with the expectations generated by one-dimensional and two-dimensional models. The ground based measurement system covers only a small part of the Earth and is limited at high latitudes.

4b. Nimbus 7 measurements appear to show a decrease in global ozone, especially at both poles. However, the decrease in Arctic ozone from 1978 to 1984 may have occurred only in the last several years. Concern exists about calibration problems, which make an exact determination of the absolute magnitude of depletion difficult. However, the latitudinal variations in depletion seem to indicate that a real phenomenon is being observed, not just instrumental drift.

4c. The cause of these apparent ozone decreases measured by Nimbus 7 has not been sufficiently analyzed to determine whether the changes (if they are real) can be attributed to manmade chemicals. Other possible explanations include natural variations caused by solar cycles or other processes. The latitudinal gradients of the changes, are, however, roughly consistent with those projected by 2-D model results, although the magnitude is substantially larger than models predict. Until further analysis is performed to determine whether depletion is actually occurring and whether it can be attributed to man-made chemicals, models to assess risks to the stratosphere should not be revised.

4d. Measurements in the Antarctic spring show that the gradual depletion that occurred in the mid-1970s over and near Antarctica has given way to a steep non-linear depletion from 1979 to 1985. The ozone maximum outside Antarctica (between 50°S and 70°S) appears to be showing a decline. The depletion of all areas south of 80°S appears to be 16 percent.

4e. Models with conventional chemistry do not predict "the Antarctic ozone hole." Care should be exercised in interpreting the meaning of the phenomenon. Several hypotheses have been put forward, including a chemical explanation that attributes the loss of ozone to manmade sources (bromine and chlorine), a chemical explanation that attributes the loss to natural sources (NOx, solar cycle), or an explanation that claims the phenomenon is entirely due to the change in climate dynamics. Until more is understood about the true causes of the hole, it is impossible to determine whether the hole is a precursor of atmospheric behavior that will occur in other regions of the world. Until a better understanding of the mechanisms creating the depletion is obtained, the existence of the Antarctic ozone hole should not be used as a basis for making regulatory decisions.

4f. This risk assessment will assume that Antarctic ozone and global trends have no implications for global projections. Future reviews should update this conclusion as necessary.

INTRODUCTION[1]

The ozone layer has a continuous distribution with a peak concentration in the lower stratosphere between about 20 and 25 kilometers altitude. [Exhibit 5-1] **illustrates the standard definitions of the troposphere, stratosphere and mesosphere in terms of the profile of temperature with altitude and shows an average ozone distribution . . . .** (NASA, 1986) Because the stratosphere constitutes a permanent inversion of air, with relatively low mixing of air with the troposphere below, the two must be viewed as two separate but related zones.

Ultraviolet solar radiation produces ozone in the atmosphere. Wave- lengths of less than 242 nm [nanometers] **possess sufficient energy to dissociate molecular oxygen, O2, into its component O atoms. These O atoms in turn react rapidly with O2 to form ozone, O3. The O3 formed can subsequently absorb ultraviolet radiation in the 200-320 nm wavelength region, dissociating into an O atom and an O2 molecule. Ozone is also dissociated, by visible and near infrared radiation, although to a much lesser extent. These processes form a long chain in which the oxygen atom alternately attaches itself to an O2 to form O3 and then is detached, until finally, the O atom and an O3 molecule react to re-form two O2 molecules . . . .** (NASA, 1986)

According to this very simple model, the ozone concentration is controlled by its production and loss rates. The ratio of the frequency of the ozone loss to production rate is directly dependent on the effective length of the chain (catalytic efficiency) and thus, the O3 concentration depends directly on the chain length . . . . (NASA, 1986)

There are chemical processes which can shorten this chain. Among these are the catalytic processes of the nitrogen, chlorine and hydrogen oxides (NOx, ClOx, HOx). These processes have the same net effect as the direct reaction of O and O3. For example, the simplest catalytic cycle for involving ClOx is the two-reaction set:

$$\begin{array}{ll} & \text{Cl + O3} \longrightarrow \text{ClO + O2} \\ & \text{ClO + O} \longrightarrow \text{Cl + O2} \\ \hline \text{Net} & \text{O + O3} \longrightarrow \text{O2 + O2} \end{array}$$

for NOx:

$$\begin{array}{ll} & \text{NO + O3} \longrightarrow \text{NO2 + O2} \\ & \text{NO2 + O} \longrightarrow \text{NO + O2} \\ \hline \text{Net} & \text{O + O3} \longrightarrow \text{O2 + O2} \end{array}$$

These sets (or cycles) are catalytic because, at the end, the Cl atom or NO molecule is again available to continue converting O and O3 back to O2. (NASA, 1986)

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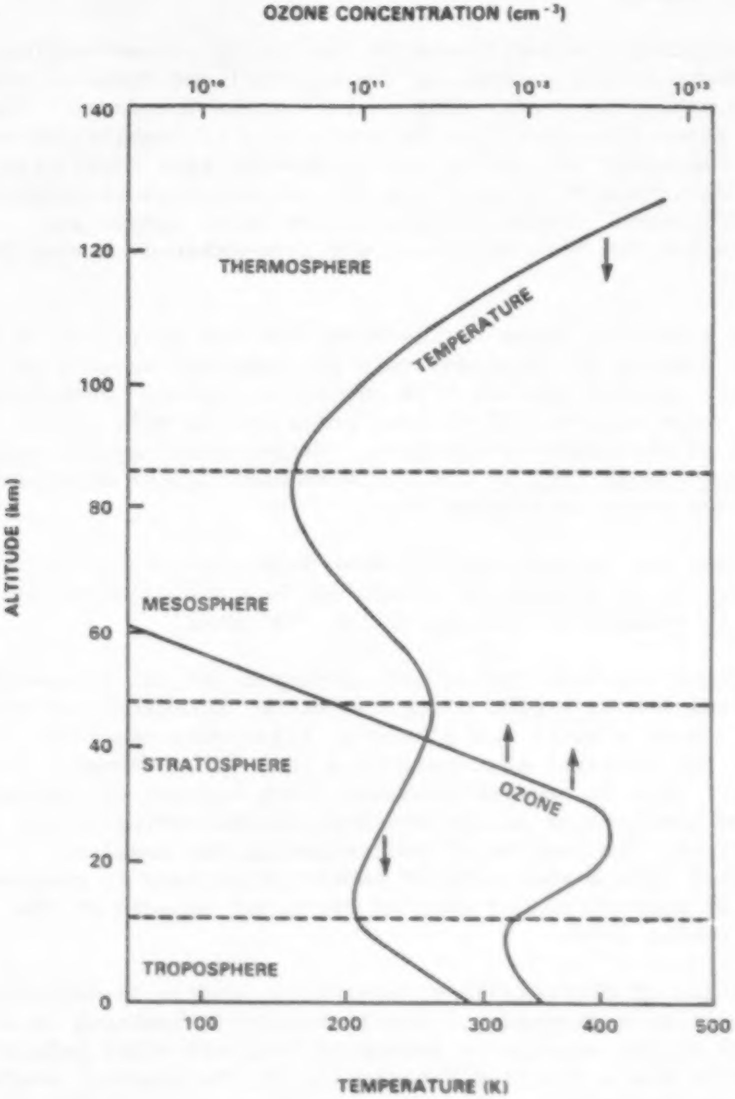
[1] Bold-face textual material is directly quoted from the source listed.

EXHIBIT 5-1

Temperature Profile and Ozone Distribution in the Atmosphere



The ozone layer has a peak concentration in the lower stratosphere between about 20 and 25 kilometers altitude. In the troposphere, temperature decreases with altitude. In the stratosphere, temperature increases with altitude.

Source: NASA (1986).

The significance of the catalytic cycles is that small amounts of the catalytic species can affect ozone in a substantial manner . . . . We now find that an even smaller amount of the catalytic oxides (in the part per billion range) are significant in controlling the amount of ozone. (NASA, 1986)

Modeling Stratospheric Change

To estimate the stratosphere's response to increasing concentrations of stratospheric perturbants requires modeling the physical and chemical forces that will bear on the catalytic cycles that control ozone abundance. Chemical interactions between gases are controlled by their rate of combination and dissociation. These reactions are controlled by kinetic rate coefficients. NASA has established an extensive program and review procedure to establish the database of rate coefficients. While subject to continual update and improvement, this database has been progressively strengthened by many years of laboratory experiments.

Radiation is also a driving force on the structure and evolution of the stratospheric system, playing an important role in chemistry as well as in the dynamics that transport various species from region to region. Uncertainties exist in some of the cross sections of various molecules as well as the energy received from the sun at different wavelengths. We refer interested readers to Chapter 7 of Atmospheric Ozone 1985 by the World Meteorological Organization (1986) for details about these uncertainties.

Transport determines how various species move from one area to another. We study species transport in an attempt to understand how the distribution and abundance of species is changed by motions of the atmosphere.

[Ideally models would simulate the actual] **structure of the stratosphere,** [which includes the] **complex interplay among radiative, dynamical and chemical processes** [described. Such a model would have a] **relatively complete description of all of the relevant processes in a three-dimensional time-dependent manner. This is not yet possible, both because of limitations in computer resources and limitations in the complete understanding of all of the relevant processes. Thus, the problem of understanding the complete stratosphere is attacked with a hierarchy of models which vary in complexity and vary in completeness of description of each of the major aspects of the atmospheric system.** (NASA, 1986)

One convenient method of classifying stratospheric models is according to their dimensionality. A zero-dimensional model considers chemistry in a box, i.e., at single points in the atmosphere decoupled from all other points. Such models (or sub-models) allow a detailed description of the chemical evolution of the system. They generally consider situations in which a chemically dominated system is driven from equilibrium. One example is the diurnal variation of the solar input which can be isolated from the complexity of the overall system so that the problem of diurnal correlation of reacting species can be evaluated. This leads to accurate computation of the modification of the effective diurnal average rate of reaction as compared to that computed from average constituent concentrations. With zero-dimensional models, the impact of changes in rate coefficients or reaction mechanisms on the chemical system are readily evaluated. Of course, care must be taken to apply these models only to chemically dominated regions of the atmosphere. (NASA, 1986)

The next level of complexity in atmospheric models is the one-dimensional model which considers variations in the vertical dimension. In this type of model, transport in the vertical dimension is parameterized as Fickian diffusion in which the same diffusion coefficient is used for each chemical species. In general, optimal values for the diffusion coefficient vs. altitude are obtained by fitting the distribution of one or more of the source gases. [Since the atmosphere exists in more than one dimension, there are various ways to interpret the output of one-dimensional models.] **... In one sense, ... one-dimensional models represent the globally and annually averaged stratosphere, in that the diffusion representation of transport attempts to account for globally averaged motions in which all horizontal motions average out ... in another sense, the models purport to represent a specific latitude (30°N) and a specific time of year (equinox) in that they use a diurnal march of zenith angles for the Sun appropriate to those conditions. Thus, the photochemical driver is not globally averaged properly, and the models represent a hybrid situation.** (NASA, 1986)

The next level of complexity in the dimensionality of atmospheric models are two-dimensional models. These models attempt to simulate the latitudinal and seasonal variations in atmospheric structure. Some of these models use specified two-dimensional transport dynamics while others seek to model the evolution of the transport by zonally averaged meridional and vertical dimensions. A characteristic difficulty with such models is how to rationally specify the transport effects of asymmetric motions. (NASA, 1986)

Three different broad classes of two-dimensional photochemical models are presently in use. These are models in which transport is accomplished by specified diffusion coefficients which are quite large. There are also those two-dimensional models with either specified or internally computed advective circulations with specified small diffusion coefficients; and finally, there are some models in which an effort is being made to use a consistent formulation of the advective and diffusive transports. (NASA, 1986)

Two-dimensional models do allow latitudinal and seasonal variations of constituents to be calculated. Thus, these features may be tested against observations for models of present-day conditions. These models also allow predictions of the latitudinal and seasonal effects of constituent scenarios to be made. Many present two-dimensional models include quite complete chemical schemes. In fact, in several cases, the chemical scheme being used in a two-dimensional model is identical to the one being used in a one-dimensional model by the same group. (NASA, 1986)

No three-dimensional (3-D) models with complete chemistry yet exist (NASA, 1986). Efforts to use general circulation models to test transport of species have been performed, but no assessments have been made with them. Thus for the purposes of this assessment, no further mention will be made of 3-D models.

Equilibrium Predictions of One-Dimensional Models

In the World Meteorological Organization (1986) assessment, a series of steady-state calculations were done with a variety of one-dimensional models. These experiments were not intended to represent simulations of future atmospheres, but to test the sensitivity of models to different changes in gases across a range of possible values. Exhibit 5-2 shows the atmospheric

EXHIBIT 5-2

Steady-State Scenarios Used in International Assessment

*SO: Definition of 1980 reference, ambient atmosphere:

Assumptions

CO2 = 340 ppm, N2O = 300 ppb, CH4 = 1.6 ppm,
CO = 100 ppb, CH3Cl = 0.7 ppb, CCl4 = 100 ppt,
CFC-11 = 170 ppt, CFC-12 = 285 ppt, CH3CCl3 = 100 ppt.
CH3Br = 20 ppt (assumed only stratospheric source of bromine),
CFC-11 flux = 309 Gg/yr = 8.4E6/cm2/sec,
CFC-12 flux = 433 Gg/yr = 1.34E7/cm2/sec.

SOA: Definition of background chlorine, circa 1960 atmosphere: Same as above without CFC-11, CFC-12, CH3CCl3.

Scenario

S1A: CFC-11 and -12 in steady state in 1980 fluxes.
*S2A: Clx = 8 ppb (approx: from CFC-11 = 0.8 ppb, CFC-12 = 2.2 ppb).
*S2B: Clx = 8 ppb plus 2 x CH4 (concentration), 1.2 x N2O.
S2C: Clx = 8 ppb plus 2 x CH4, 1.2 N2O and 2 x CO2.
*S3A: Clx = 15 ppb (approx: from CFC-11 = 1.6 ppb, CFC-12 = 4.4 ppb).
*S3B: Clx = 15 ppb plus 2 x CH4 (concentration), 1.2 x N2O.
S3C: Clx = 15 ppb plus 2 x CH4, 1.2 x N2O, and 2 x CO2.
S4: 1980 with 2 x CH4 concentration.
S5: 1.2 x N2O.
S6: 2 x CO.
S7: 2 x CO2.
S8: NOx injection from stratospheric aircraft 1,000 molec cm-3S-1 or 2,000 molec cm-3S-1 at 17 km and 20 km.
S9: Bromine increase from 20 ppt to 100 ppt.

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* Also used as 2-D model scenario.

A set of scenarios for the future evolution of the atmosphere was selected by the World Meteorological Organization for 1-D and 2-D model simulations of stratospheric ozone. Each scenario has a label. For instance, S1A refers to the scenario in which equilibrium concentrations are reached for CFC-11 and -12 without increases in other gases.

Source: Adapted from World Meteorological Organization (1986).

concentrations used in various "steady-state scenarios" of different trace gas levels. Exhibits 5-3, 5-4, and 5-5 show the effect of these trace gas levels on globally averaged ozone depletion. Exhibits 5-6, 5-7, and 5-8 show the importance of odd nitrogen on projected ozone depletion, the effects of doubled carbon dioxide on temperature, and the changes in vertical distribution of ozone. The following conclusions can be made based on those modeling experiments:

- different models of ozone depletion are roughly consistent in projections of ozone depletion.
- projections of ozone depletion resulting from chlorine increases are decreased when carbon dioxide, methane, and nitrous oxide are added to future atmospheres.
- projected ozone depletion at 40 kilometers is much higher than column average.
- even if chlorine levels are held to 8 ppb and other gases increase, the abundance of ozone at different altitudes would be fundamentally changed, with ozone increases at lower altitudes and decreases in upper altitudes.
- carbon dioxide concentration increases are expected to cool the stratosphere, reducing ozone depletion.
- uncertainties in odd nitrogen in the stratosphere have critical importance in estimating projected depletion.

Bromine

. . . Although bromine chemistry is in many respects similar to that for chlorine, there are also significant differences. Dissociation and reactions of CH3Br and other important bromine sources occur at lower altitudes than for the major chlorine sources. While the reaction of Cl with CH4 to produce HCl limits the abundance of active chlorine radical species in the stratosphere, the reaction of Br with CH4 is endothermic and therefore negligibly slow. Also, the photolysis of HBr is more rapid than that of HCl, and the reaction of OH with HBr is more rapid than its rate with HCl. Consequently, the majority of BrX is present as the active species BrO. On a molecule for molecule basis, bromine is a much more efficient sink for stratospheric odd oxygen than chlorine. (World Meteorological Organization, 1986)

The bromine . . . sensitivity test considered is an increase in surface mole fraction of CH3Br from 20 to 100 pptv. As seen in [Scenario S9 of Exhibit 5-5] **the LLNL model was the only model used to calculate the perturbation. It gave a total ozone change of -3% (without temperature feedback), in good agreement with the -4% calculated change in total ozone for the same scenario by Prather et al. (1984). The major contribution to the change in the ozone column occurs around 20 km. The largest relative change in ozone (7% decrease) is at 15 km with a secondary peak at about 40 km.** (World Meteorological Organization, 1986)

EXHIBIT 5-3

Change in Total Ozone from Representative One-Dimensional Models for Steady-State Scenarios Containing Clx Perturbations

		Change in Total Ozone (%)					
Scenario		LLNL (Wuebbles)	Harvard (Prather)	AER (Sze)	DuPont (Owens)	IAS (Brasseur)	MPIC (Bruehl)
S1A	CFC 1980 Flux only	-7.0 (-7.2)	-5.3	-5.3	-4.9 (-6.1)	(-7.9)	(-9.4)
S2A	8 ppbv Clx only	-5.1 (-5.7)	-2.9	-4.6		(-4.1)	(-9.1)
S2B	8 ppbv Clx + 2 x CH4 + 1.2 x N2O	-3.4	-3.0	-3.3	-3.1	(-2.3)	(-6.0)
S2C	8 ppbv Clx + 2 x CH4 + 1.2 x N2O + 2 x CO2	(+0.2)			(-1.4)	(0.0)	(-5.2)
S3A	15 ppbv Clx only	-12.2 (-12.4)	-17.8	-15.		(-8.8)	(-22.0)
S3B	15 ppbv Clx + 2 x CH4 + 1.2 x N2O	-7.8 (-7.2)	-8.2	-8.8	-7.2	(-5.6)	(-13.7)
S2C	15 ppbv Clx + 2 x CH4 + 1.2 x N2O + 2 x CO2	(-4.6)				(-3.5)	(-13.6)

Calculated ozone changes from six modeling groups participating in international assessment. Results are from 1-D models and are relative to an atmosphere with about 1.3 ppb background Clx and with no CFCs (Scenario # SOA). Numbers in parentheses refer to calculated changes when including temperature feedback.

Source: World Meteorological Organization (1986).

EXHIBIT 5-4

Change in Total Ozone at 40 kilometers for Steady-State Scenarios Containing Clx Perturbations

	Change in 40 km Ozone (%)					
Scenario	LLNL (Wuebbles)	Harvard (Prather)	AER (Sze)	DuPont (Owens)	IAS (Brasseur)	MPIC (Bruehl)
S1A CFC 1980 Flux only	-63 (-56)	-64	-62	-62 (-57)	(-81)	(-59)
S2A 8 ppbv Clx only	-55 (-50)	-57	-56		(-67)	(-57)
S2B 8 ppbv Clx + 2 x CH4 + 1.2 x N2O	-50 (-45)	-50	-49	-58	(-62)	(-50)
S2C 8 ppbv Clx + 2 x CH4 + 1.2 x N2O + 2 x CO2	(-35)			(-49)	(-55)	(-45)
S3A 15 ppbv Clx-only	-74 (-68)	-78	-77		(-83)	(-76)
S3B 15 ppbv Clx + 2 x CH4 + 1.2 x N2O	-69 (-64)	-73	-64	-74	(-81)	(-71)
S2C 15 ppbv Clx + 2 x CH4 + 1.2 x N2O + 2 x CO2	(-58)				(-78)	(-67)

Calculated changes in upper stratospheric ozone (40 kilometers) from six modeling groups participating in international assessment. Results are from 1-D models and are relative to an atmosphere with about 1.3 ppb Clx and with no CFC (Scenario # SOA). Numbers in parentheses refer to calculated changes when including temperature feedback.

Source: World Meteorological Organization (1986).

EXHIBIT 5-5

Change in Total Ozone for Steady-State Scenarios

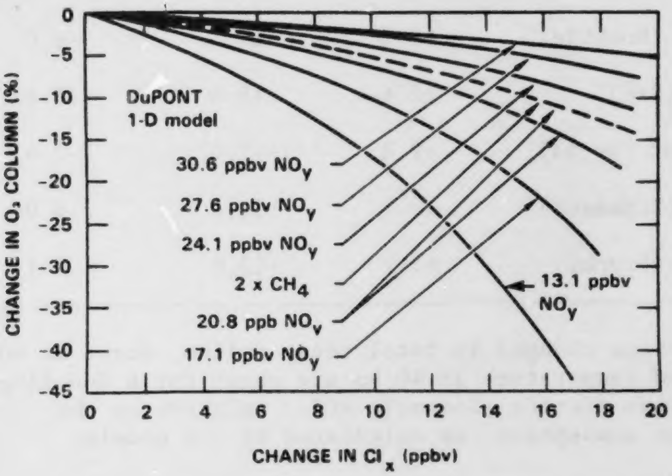
		Change in Total Ozone (%)					
Scenario		LLNL (Wuebbles)	Harvard (Prather)	AER (Sze)	DuPont (Owens)	IAS (Brasseur)	MPIC (Bruehl)
S4	2 x CH4	+2.0 (+2.9)	+0.3	+0.9	+1.7	(+1.6)	(+1.4)
S5	1.2 x N2O	-2.1 (-1.7)	-2.6	-1.8	-2.3	(-1.1)	(-1.2)
S6	2 x CO	+1.1 (+1.1)	+0.3	+0.6	+0.8		(+0.8)
S7	2 x CO2	(+3.5)		(+2.6)	(+2.8)	(+3.1)	(+1.2)
S8a	NOx, injection 17 km, 1,000 molec. cm-3s-1	-1.8 (-1.3)				(-1.4)	
S8b	NOx, injection 17 km, 2,000 molec. cm-3s-1	-5.7				(-3.4)	
S8c	NOx, injection 20 km, 1,000 molec. cm-3s-1	-5.7 (-4.6)				(-3.9)	
S8d	NOx, injection 20 km, 2,000 molec. cm-3s-1	-12.2				(-8.8)	
S9	Brx 20 to 100 pptv	-3.0					

Calculated ozone changes from six modeling groups participating in international assessment. Results are from 1-D models and are relative to the present atmosphere (Scenario #S0), except for the AER and DuPont calculations, which are relative to a background atmosphere with no CFCs (Scenario #SOA). Numbers in parentheses refer to calculated changes when including temperature feedback.

Source: World Meteorological Organization (1986).

EXHIBIT 5-6

Effect of Stratospheric Nitrogen (NOy) on Chlorine-Induced Ozone Depletion



Results from Owens and Fisher of Dupont. Calculated ozone change is presented as a function of stratospheric Clx for different values of stratospheric NOy (NO, NO2, NO3, N2O5, ClONO2, NHO4, and HNO3). For large background NOy (about 30 ppb) the decrease of ozone is small and very nearly linear with increasing Clx, but for small background NOy (13 ppb), ozone is strongly and non-linearly reduced by Clx.

Source: World Meteorological Organization (1986).

EXHIBIT 5-7

Effect of Doubled CO2 Concentrations on Ozone Temperature

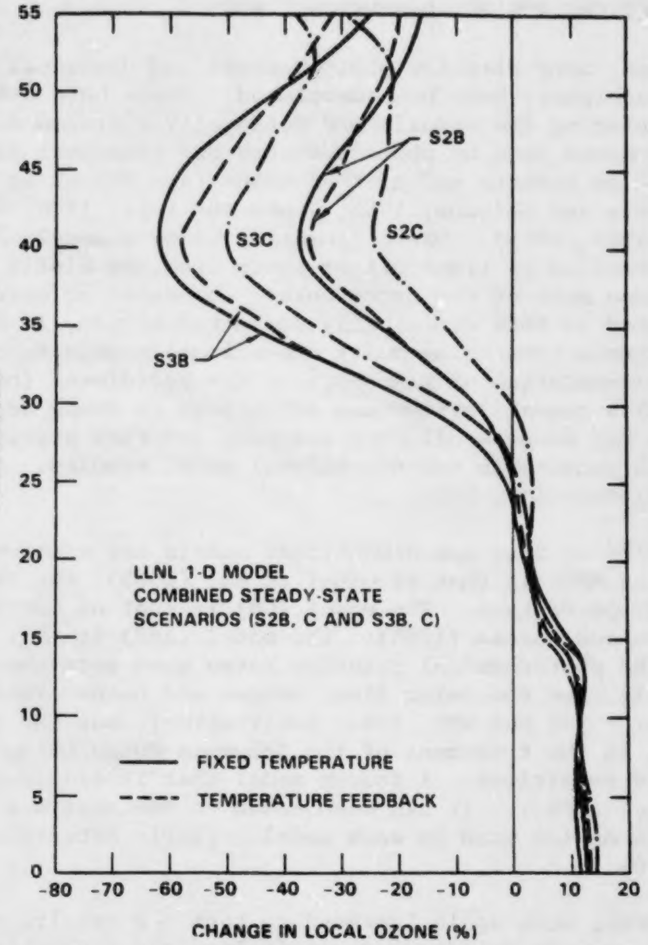
One-Dimensional Models	Ozone Column (Percent)	Ozone at 40 km (Percent)	Temp. at 40 km (Kelvin)
LLNL (Wuebbles)	+3.5	+19.3	-8.0
AER (Sze)	+2.6	+9.4	-8.4
DuPont (Owens)	+2.8	+11.5	-7.4
IAS (Brasseur)	+3.1	+18.8	-9.0
MPIC (Bruehl)	+1.2	+13.0	-7.1

Percentage changes in total ozone column, ozone at 40 km, and temperature at 40 km are shown for a doubling of carbon dioxide (Scenario #S7), relative to the present atmosphere, as calculated by 1-D models.

Source: World Meteorological Organization (1986).

EXHIBIT 5-8

Calculated Changes in Ozone Versus Altitude



Changes in vertical distribution of ozone for steady-state changes in ozone as calculated by the LLNL 1-D model for the following scenarios:

S2B: Clx = 8 ppb plus 2 x CH4 (concentration), 1.2 x N20
S2C: Clx = 8 ppb plus 2 x CH4, 1.2 x N20, and 2 x CO 2
S3B: Clx = 15 ppb plus 2 x CH4, 1.2 x N20
S3C: Clx = 15 ppb plus 2 x CH4, 1.2 x N20, and 2 x CO2.

Source: World Meteorological Organization (1986).

Because current increases in concentrations of Halon 1211 are at 23 percent per year, and, in the absence of regulation, emissions may increase greatly, bromine from Halon molecules constitute a larger risk for stratospheric depletion than generally recognized.

EQUILIBRIUM PREDICTIONS FOR TWO-DIMENSIONAL MODELS

In recent years, many detailed photochemical and dynamical two-dimensional models of the stratosphere have been developed. These have achieved a measure of success in simulating the zonally and seasonally averaged distribution of constituents influenced both by photochemistry and transport in the stratosphere, such as methane and nitrous oxide (see Miller et al., 1981; Gidel et al., 1983; Garcia and Solomon, 1983; Jones and Pyle, 1984; Guthrie, et al., 1984; Ko et al., 1984, 1985). Ozone densities below about 20-25 km are predominantly controlled by transport of ozone from the middle and upper stratosphere. Since most of the ozone column abundance at extra-tropical latitudes is located in this dynamically dominated region, it is important to examine ozone perturbations using multi-dimensional models that include at least a first order representation of transport in the meridional (height-latitude) plane. Such studies reveal latitudinal variations in ozone depletions, which are of importance for ozone monitoring programs and they provide insight beyond that obtained with comparable one-dimensional model studies. (World Meteorological Organization, 1986)

Here the results of four two-dimensional models are examined. **The model referred to here as MPIC is that of Gidel et al. (1983); the calculations were done by Schmailzl and Crutzen. The model (GS) is that of Garcia and Solomon (1983) and Solomon and Garcia (1984). The model (AER) is that described by Ko** et al. [1985]. **The photochemical reaction rates used were those of JPL/NASA (1985) [Appendix 1], and the solar flux, oxygen and ozone cross sections were taken from Chapter 7** [of the WMO, 1986, publication], **but the authors used different methods in the treatment of the Schumann-Runge bands and used different boundary conditions.** A fourth model that is examined (IS) is that of Isaksen and Stordal (1986). It has been added to the analyses in Exhibit 5-9 which **shows the scenarios used in each model.** (World Meteorological Organization, 1986)

These experiments were again intended to test the results of the models across a range of species values, not to simulate the atmosphere in any given year. Exhibits 5-10 through 5-21 provide detailed results of these experiments. The conclusions are briefly summarized here:

- 2-D models get roughly the same global depletion for the same inputs.

- 2-D models agree in projecting more depletion near the poles than at the equator, but vary in the strength of this latitudinal effect.

- Winter and Spring are the seasons of greatest projected depletion.

EXHIBIT 5-9

Two-Dimensional Model Scenarios Used in International Assessment

	Cl_x/ppb			2xCH_4		
Scenario #	Total	Reference	Increase	1.2xN_2O	Model	Symbol
S2A	8.	1.3	6.7	no	Garcia and Solomon (1983)	GS
S2A	8.2	1.3	6.9	no	Ko et al. (1985)	AER
S3A	15.5	1.3	14.2	no		AER
S2C	8.	1.3	6.7	yes	Garcia and Solomon (1983)	GS
SMA	9.5	2.7	6.8	no	Gidel et al. (1983)	MPIC
-	2.7	1.3	1.4	no		MPIC
-	9.5	1.3	8.2	no		MPIC
SMB	9.5	2.7	6.8	yes		MPIC
SMC	18.	2.7	15.3	yes		MPIC
IS	7.2	1.0	6.2	no	Isaksen and Stordal (1986)	IS

Scenarios used for 2-D model simulations of stratospheric ozone. The GS, AER, and MPIC models were used in the WMO international assessment. The IS model has been added for this analysis.

Source: Adapted from World Meteorological Organization (1986).

EXHIBIT 5-10

2-Dimensional Model Results:
Global and Seasonally-Averaged Ozone Depletion

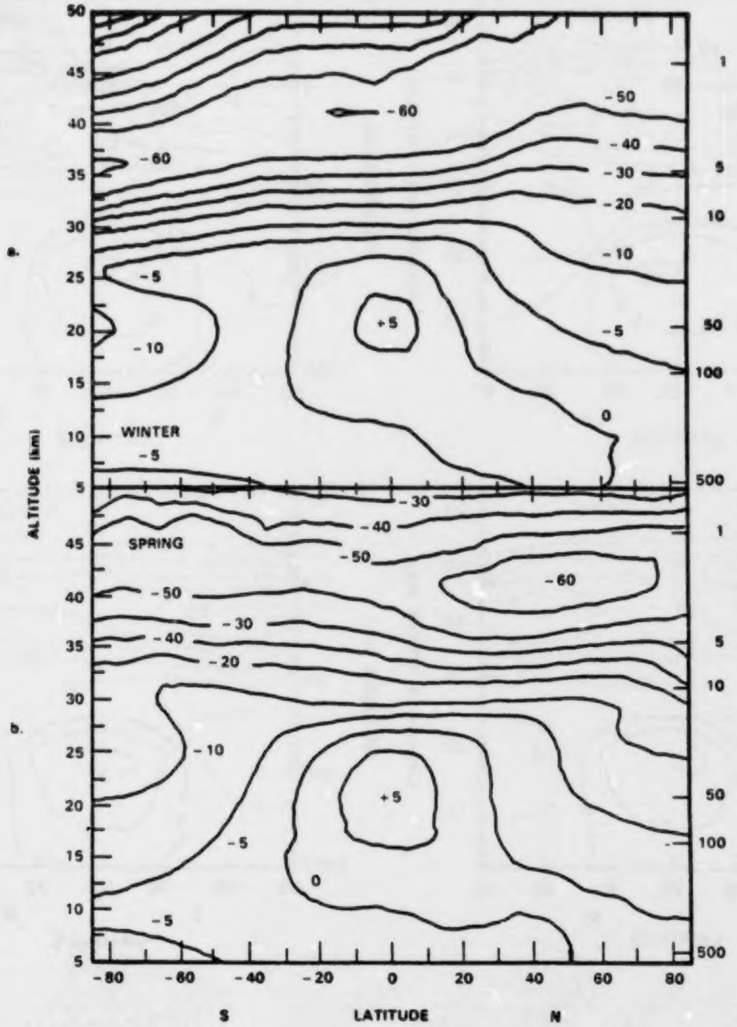
Clx/ppbv Initial	Clx/ppbv Final	Clx/ppbv Increase	2 x CH4 1.2 x N2O	% Ozone Decrease	Model Sensitivity -%/ppbv	Model
1.3	2.7	1.4	no	1.9	1.36	MPIC
2.7	9.5	6.8	no	7.2	1.06	
1.3	9.5	8.2	no	9.1	1.11	
2.7	9.5	6.8	yes	4.5	0.66	MPIC
2.7	18.	15.3	yes	11.1	0.73	
1.3	8.2	6.9	no	8.5	1.23	AER
1.3	15.5	14.2	no	18.	1.27	
1.0	7.2	6.2	no	7.1	1.16	IS

Results for 2-D models used in international assessment. Model sensitivity of ozone to Clx is percent ozone decrease divided by ppb Clx increase.

Source: World Meteorological Organization (1986).

EXHIBIT 5-11

Ozone Depletion by Latitude, Altitude, and Season for Clx Increase of 6.8 ppbv (MPIC 2-D Model)

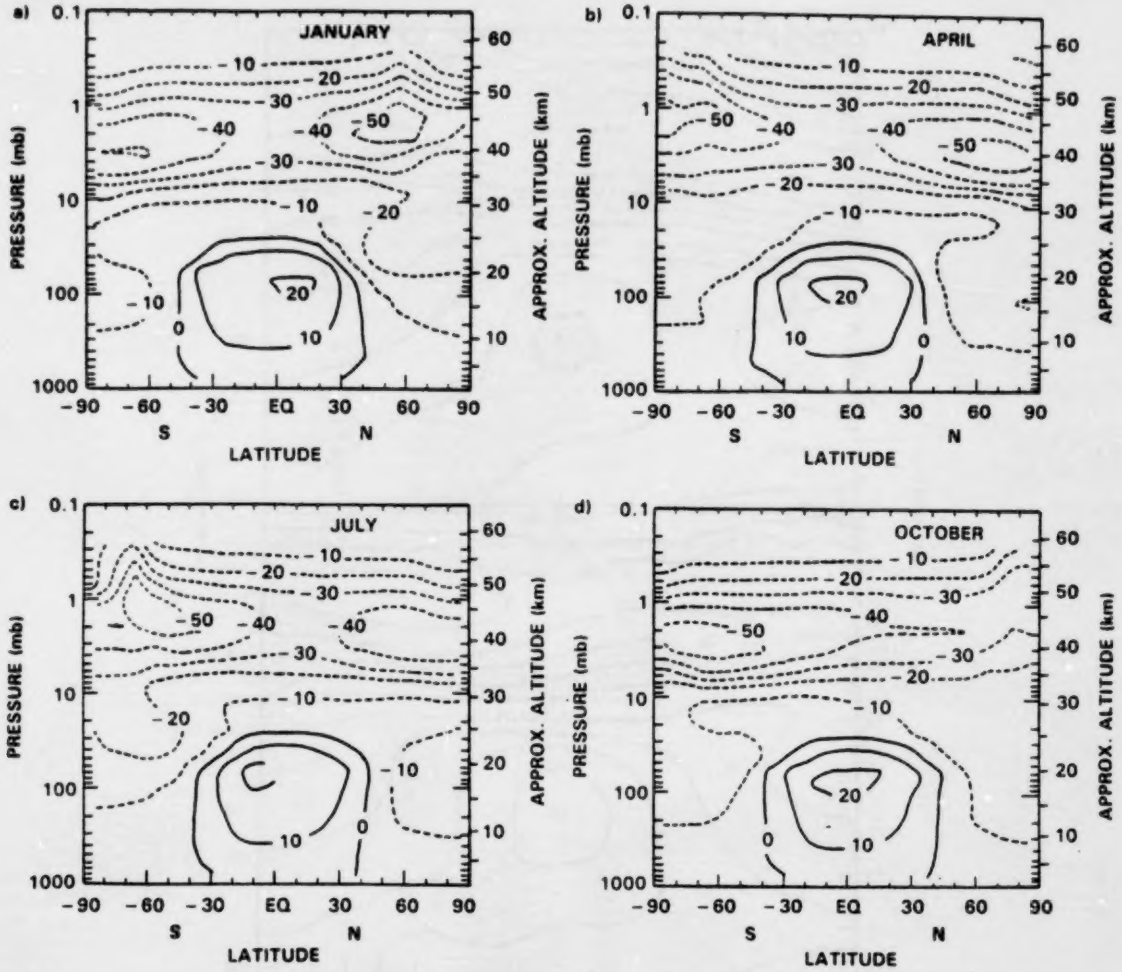


Results from MPIC 2-D model, for scenario #SMA, relative to reference atmosphere with 2.7 ppb Clx (see Exhibit 5-9). Panel a shows percent change in ozone in winter; panel b in spring.

Source: World Meteorological Organization (1986).

EXHIBIT 5-12

Ozone Depletion by Latitude, Altitude, and Month for Clx Increase of 6.8 ppbv (AER 2-D Model)

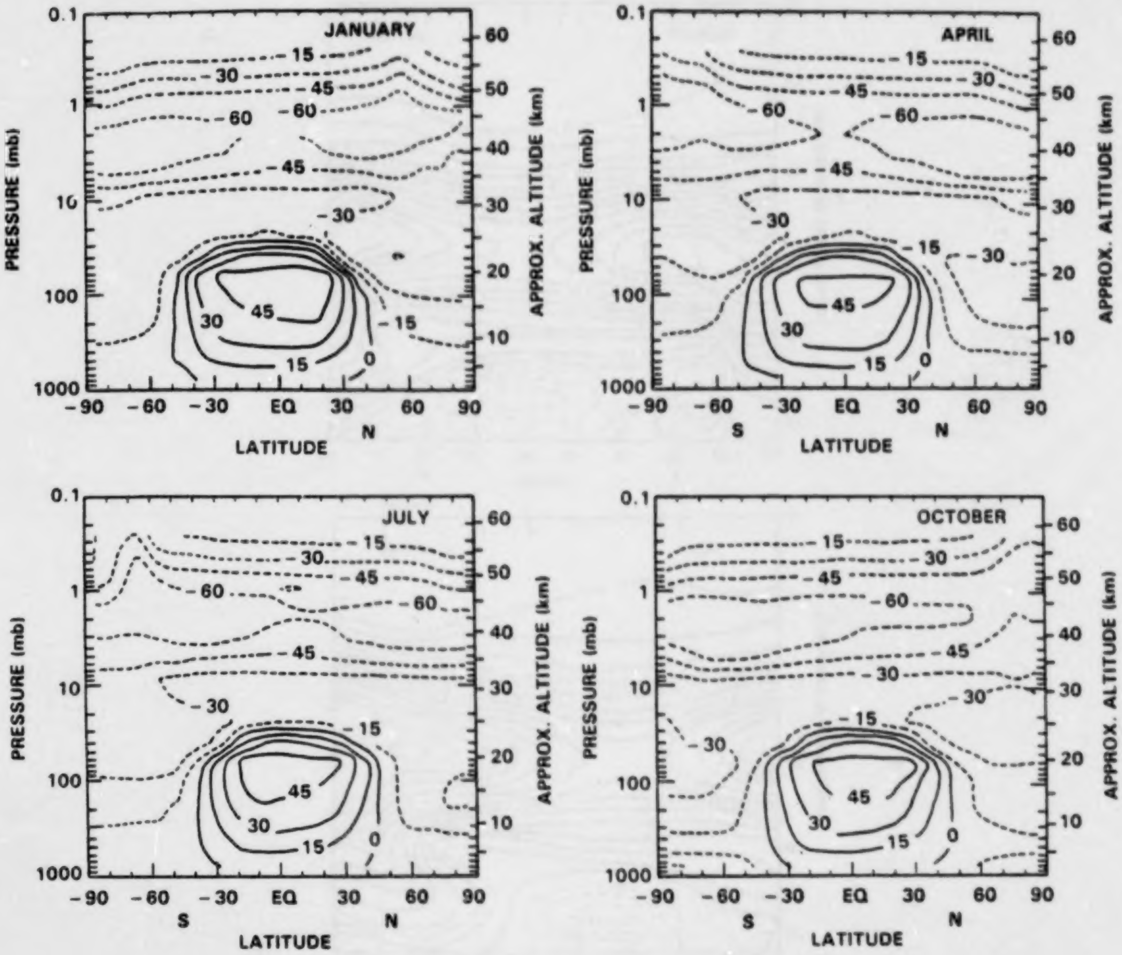


Results from AER 2-D model, for scenario #S2A, relative to reference atmosphere with 1.3 ppb Clx (see Exhibit 5-9). Panel a shows percent change in ozone in January, panel b in April, panel c in July, and panel d in October.

Source: World Meteorological Organization (1986).

EXHIBIT 5-13

Ozone Depletion by Latitude, Altitude, and Month for CLx Increase of 14.2 ppbv (AER 2-D Model)

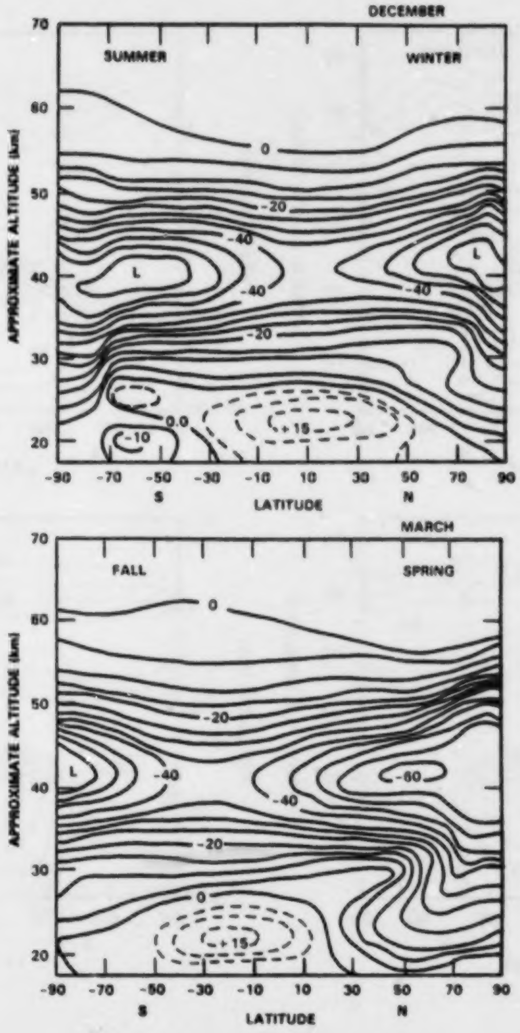


Results from AER 2-D models, for scenario #S3A, relative to reference atmosphere with 1.3 ppb Clx (see Exhibit 5-9). Panel a shows percent change in ozone in January, panel b in April, panel c in July, and panel d in October.

Source: World Meteorological Organization (1986).

EXHIBIT 5-14

Ozone Depletion by Latitude, Altitude, and Month for Clx Increase of 6.8 ppbv (GS 2-D Model)



Results from GS 2-D models, for scenario #S2A, relative to reference atmosphere with 1.3 ppb Clx (see Exhibit 5-9). Top panel shows percent changes in ozone in December, and bottom panel in March.

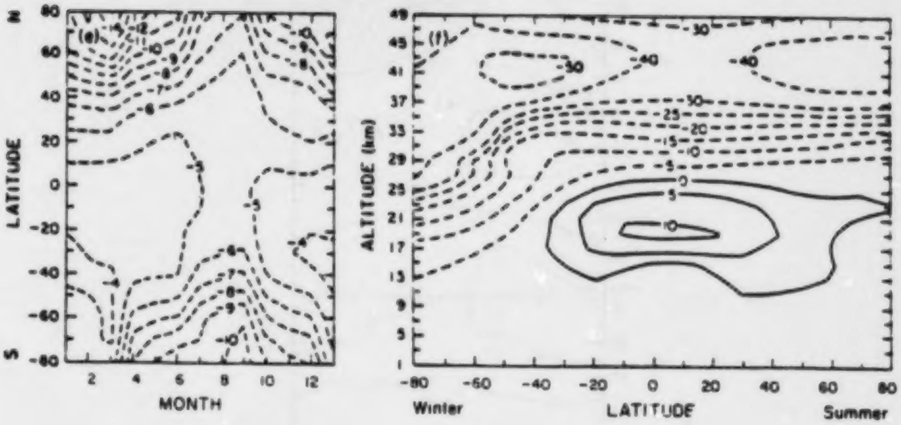
Source: World Meteorological Organization (1986).

EXHIBIT 5-15

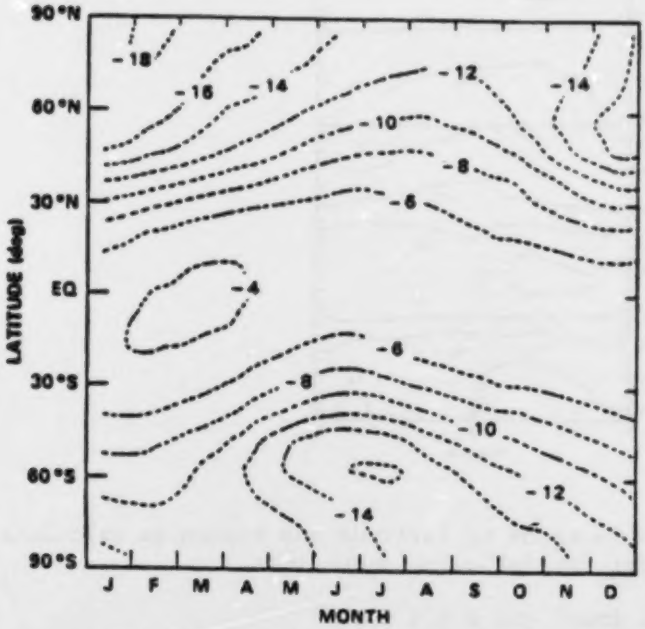
Ozone Depletion by Latitude and Season
for CLx Increase of 6.0 ppv
(IS 2-D Model)
(AER 2-D Model)

Isaksen:

CFC Releases,
1980 Production,
Steady State



AER:

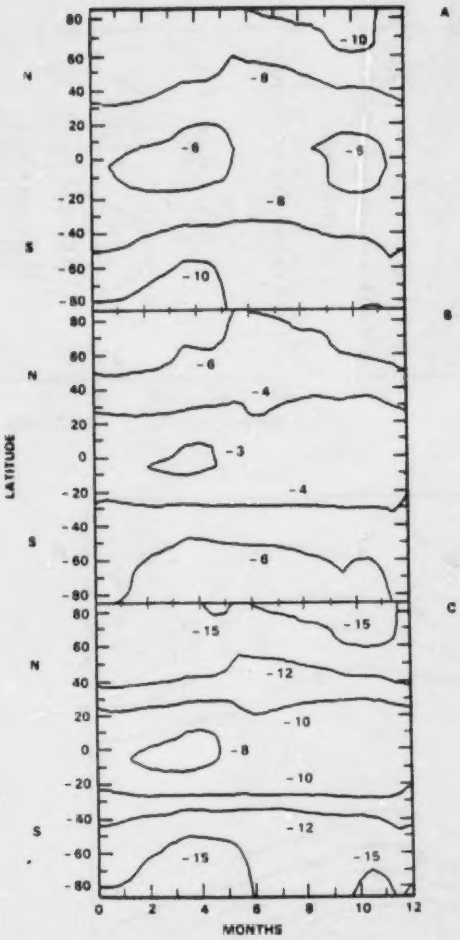


Results from IS 2-D model, for an increase in Clx from 1.0 ppbv to 7.2 ppbv. The bottom panel depicts changes of 1.3 to 8.2 ppbv Clx for the AER 2-D model. Both panels show change in the total ozone column as a function of latitude and time of the year.

Source: Isaksen and Stordal (1986); WMO (1986).

EXHIBIT 5-16

Change in Ozone by Latitude and Season for Clx Perturbations (MPIC 2-D Model)



Steady-state changes in ozone by latitude and season as calculated by the MPIC 2-D model for the following scenarios:

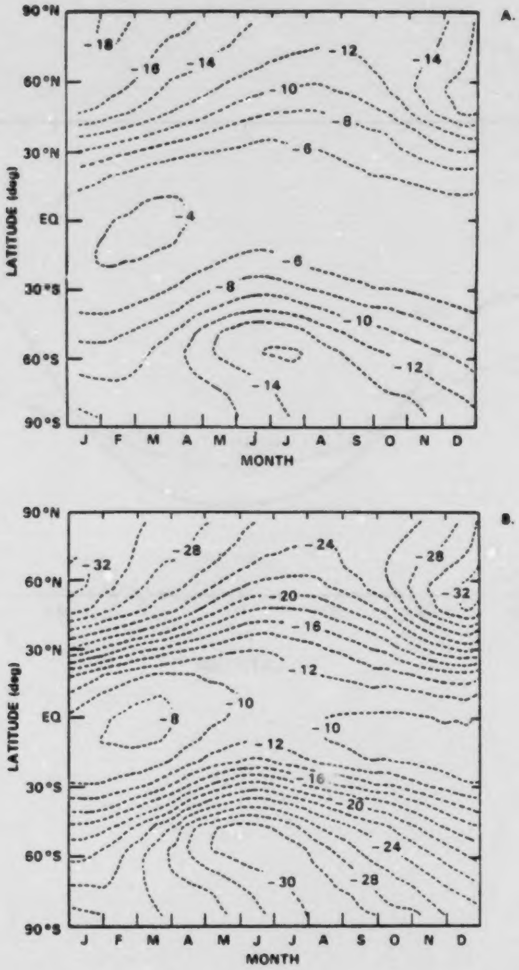
Panel A, Scenario SMA: Clx = 9.5 ppbv
Panel B, Scenario SMB: Clx = 9.5 ppbv plus 2 x CH_4, 1.2 x N_2O
Panel C, Scenario SMC: Clx = 18.0 ppbv plus 2 x CH_4, 1.2 x N_2O

Changes are relative to reference atmosphere with 2.7 ppbv.

Source: World Meteorological Organization (1986).

EXHIBIT 5-17

Change in Ozone by Latitude and Season for Clx Perturbations (AER 2-D Model)



Steady state changes in ozone by latitude and season as calculated by the AER 2-D model for the following scenarios:

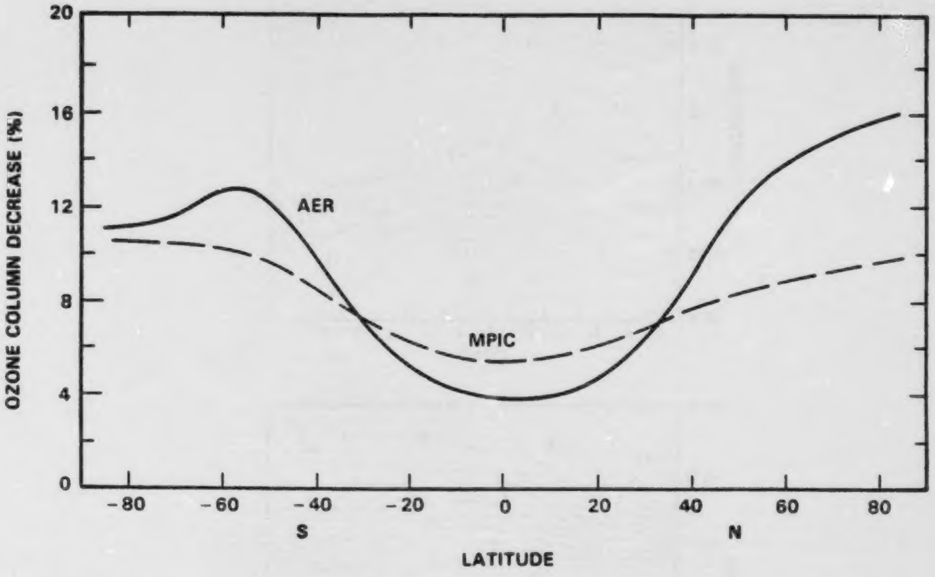
Panel A, Scenario S2A: Clx = 8.2 ppbv
Panel B, Scenario S3B: Clx = 15.5 ppbv

Changes are relative to reference atmosphere with 1.3 ppbv Clx. The global average ozone changes are -8.5 percent and -18 percent, respectively.

Source: World Meteorological Organization (1986).

EXHIBIT 5-18

Latitudinal Dependence of AER and MPIC 2-D Models

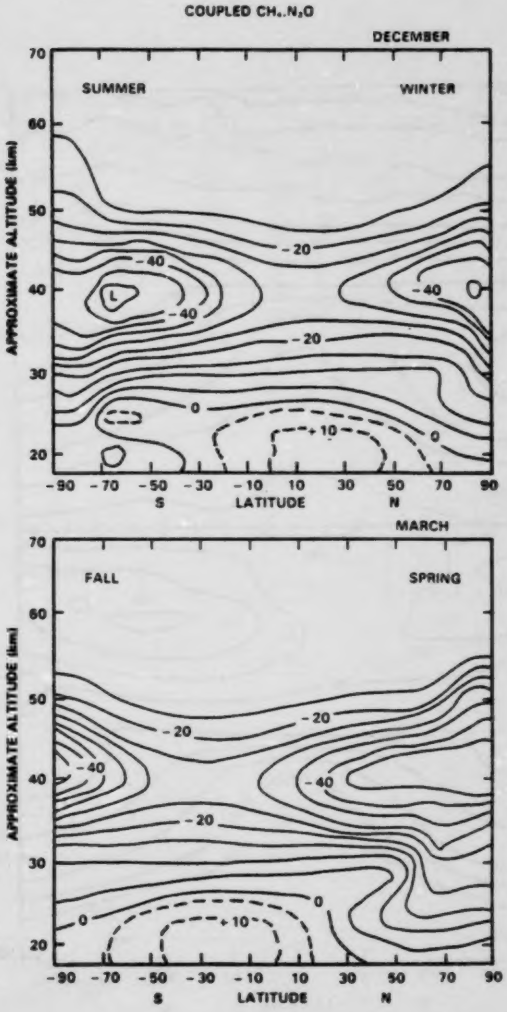


Ozone column decrease in April for Clx increase of about 7 ppbv. The AER 2-D model shows more variation with latitude than the MPIC model. This difference can be attributed to differences in transport, especially the rate of horizontal mixing.

Source: World Meteorological Organization (1986).

EXHIBIT 5-19

Change in Ozone by Latitude, Altitude, and Month for Coupled Perturbations (GS 2-D Model)

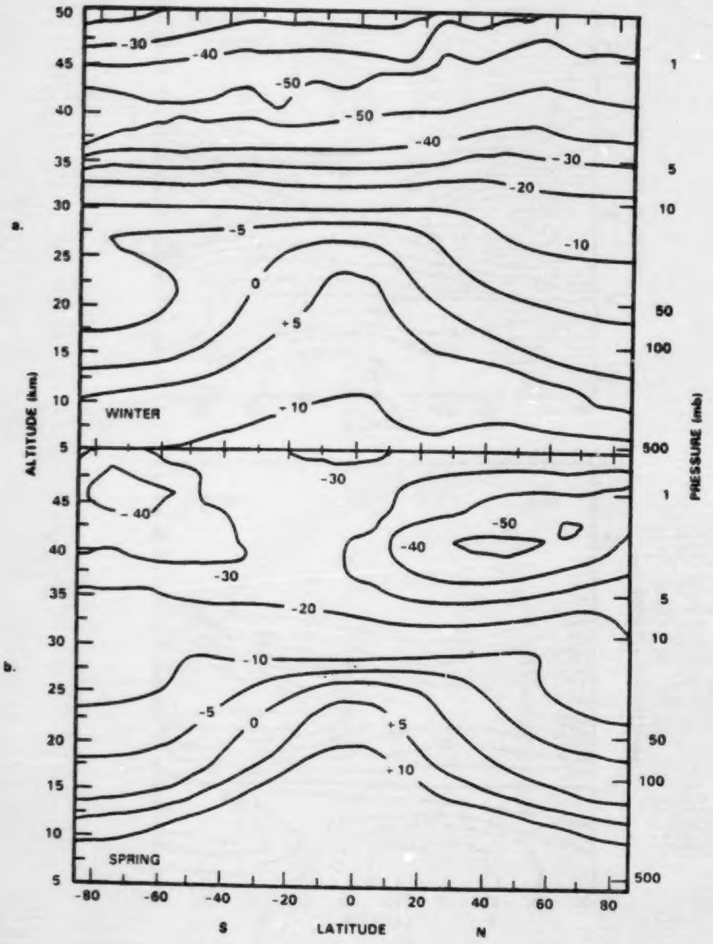


Steady-state changes in ozone by latitude and altitude as calculated by the GS 2-D model. For Scenario S2C: Clx = 8 ppbv plus 2 x CH_4 and 1.2 x N_2O. Top panel shows results for December, bottom panel for March. Changes are relative to reference atmosphere with 1.3 ppbv Clx.

Source: World Meteorological Organization (1986).

EXHIBIT 5-20

Changes in Ozone by Latitude, Altitude, and Season for Coupled Perturbations (MPIC 2-D Model)

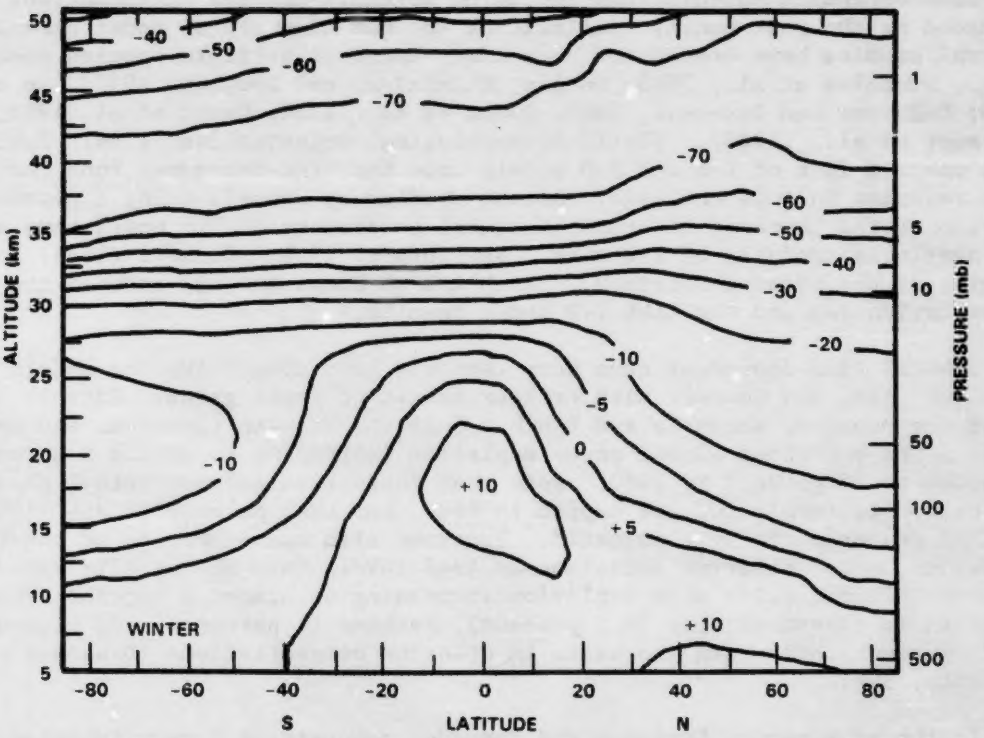


Steady-state changes in ozone by latitude and altitude as calculated by the MPIC 2-D model. For Scenario SMB: Clx = 9.5 ppbv plus 2 x CH_4 and 1.2 x N_2O. Panel a shows results for winter, panel b for spring. Changes are relative to reference atmosphere with 2.7 ppbv Clx.

Source: World Meteorological Organization (1986).

EXHIBIT 5-21

Changes in Ozone by Latitude and Altitude in Winter for Coupled Perturbations (MPIC 2-D Model)



Steady-state changes in ozone by latitude and altitude in winter as calculated by the MPIC 2-D model for Scenario SMC: ClO - 15.3 ppbv plus 2 x CH4 and 1.2 x N2O. Changes are relative to reference atmosphere with 2.7 ppbv ClO.

Source: World Meteorological Organization (1986).

- multi-species perturbations in which methane concentrations are increased in addition to the chlorine increases still result in column ozone depletion, but with the loss of ozone varying at different altitudes and by different amounts in different models.

TIME-DEPENDENT PREDICTIONS FOR ONE-DIMENSIONAL MODELS FOR DIFFERENT SCENARIOS OF TRACE GASES

Time-dependent calculations including multiple-species perturbations are regarded as the most nearly realistic of the one-dimensional model assessments. Several studies have considered such time-dependent multiple-species scenarios (e.g., Wuebbles et al., 1983; Callis, Natarajan, and Boughne, 1983; Sze et al., 1983; DeRudder and Brasseur, 1984; Owens et al., 1984; Owens et al. 1985; Brasseur et al., (1985). (World Meteorological Organization, 1986) Exhibit 5-22 shows a list of 1-D and 2-D models used for time-dependent runs that have been reported in this analysis. Recent studies by Connell using a parameterized version of the Lawrence Livermore National Laboratory (LLNL) model have added to the available analysis of 1-D runs. See Chapter 17 and Connell (1986) for details of the parameterization. Exhibit 5-23 shows the fit between the Connell parameterization and the LLNL 1-D model results.

Several time-dependent runs have recently been done using the models of Brasseur, AER, and Connell with greater levels of trace gases. Exhibit 5-24 shows the Brasseur scenario and Exhibit 5-25 the results (Brasseur and DeRudder, 1986). The run shows global ozone depletion increasing to around 5 percent by 2040 and to 30 percent by 2080. Note that these runs assumed methyl chloroform and carbon tetrachloride are capped in 1986, and that Halon-1211 and -1301 and HCFC-22 are essentially eliminated. Brasseur also ran scenarios of constant CFC emissions, other chlorine emissions at 1985 levels (and Halons eliminated). The results (Exhibit 5-26) show depletion increasing to almost 2 percent before the increase in carbon dioxide (0.5 percent), methane (1 percent), and nitrous oxide (0.25 percent) overwhelm increases in chlorine concentrations (Brasseur and DeRudder, 1986).

In the same paper, Brasseur and DeRudder demonstrate a very important sensitivity of the models to representation of radiative processes. Exhibit 5-27 summarizes the results. Clearly, the different radiative codes produce different depletion estimates. Brasseur points out that the differences in radiative code may explain differences in 1-D model calculations in the World Meteorological Organization (1986) report. In Exhibit 5-28, the results of Connell's parameterization and Brasseur's model are presented. Connell's results, which are lower, are based on a model that uses an assumption of fixed equilibrium temperature for regions above 14 km and fixed temperature below. It is possible that Brasseur may be correct in his assertion that differences in model results may stem from this assumption. In general, one might expect the approach used by Brasseur in the model C.1 (that is, not assuming fixed equilibrium temperatures) to be more likely to describe the real world, since radiative equilibrium is not likely to prevail in that region with ozone changes. Brasseur does point out, however, that both radiative models do as well in explaining the current atmosphere.

EXHIBIT 5-22

Models With Reported Time-Dependent Runs

Wuebbles (Lawrence Livermore National Laboratory [LLNL] Model) 1-D

Connell (Parameterization of Lawrence Livermore National Laboratory) 1-D

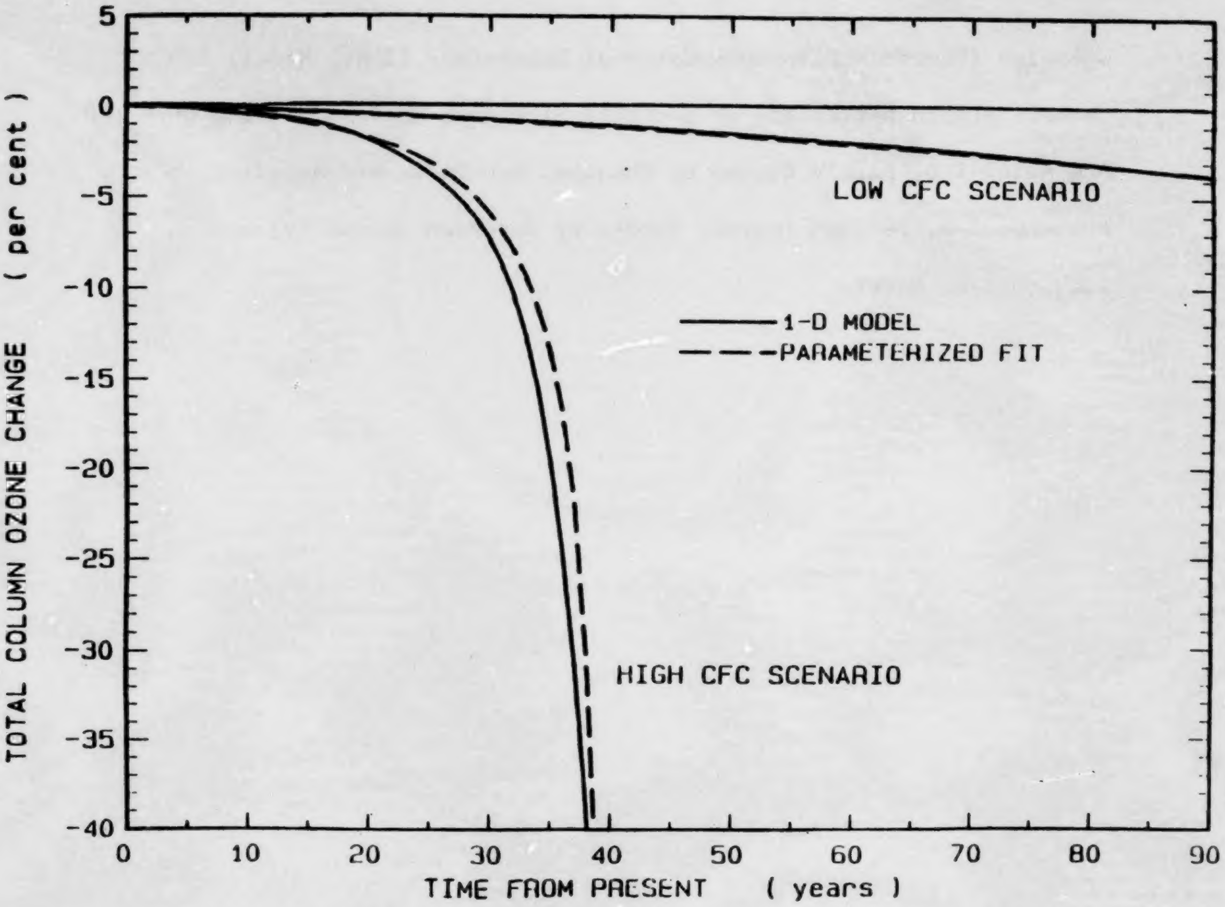
AER Model 1-D, partly funded by Chemical Manufacturers Association

Brasseur 1-D, Belgium (partly funded by European Community)

Isaksen 2-D, Norway

EXHIBIT 5-23

LLNL 1-D Model versus Parameterized Fit



Time-dependent change in ozone as calculated by LLNL 1-D model and parameterized fit for two divergent scenarios of growth in CFCs and other trace gases. "Differences between the parameterization and the full 1-D model are generally less than one percent except at very large depletions."

Source: Connell (1986).

EXHIBIT 5-24

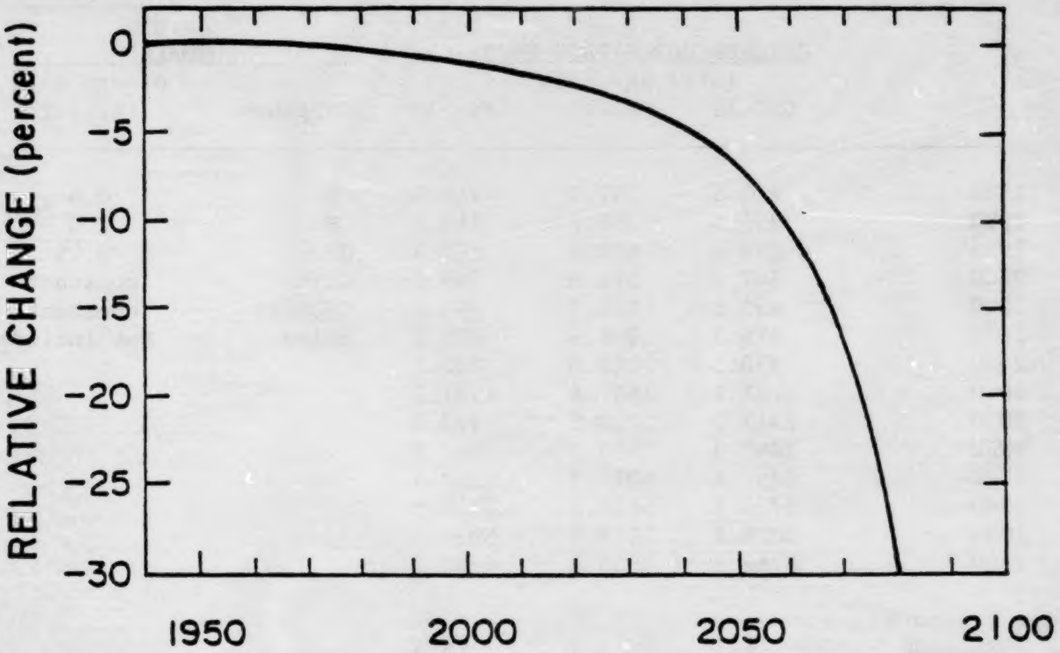
Trace Gas Assumptions for Results in Exhibit 5-25 (Brasseur and DeRudder 1-D Model, 1986)

	CHLOROFLUOROCARBON EMISSIONS (mill kg/year)			OTHERS	
	CFC-11	CFC-12	CFC-113	Compound	Growth Rate (%/year)
1985	279.5	397.0	148.4	CO2	-0.5
1990	253.5	396.2	198.6	CH4	1.0
1995	298.0	450.6	265.7	N2O	0.25
2000	347.7	514.8	347.7	CCl4	constant
2010	455.8	665.7	465.8	CH3CCl3	constant
2020	615.3	898.6	615.3	Halons	Not included
2030	830.5	1213.0	830.5		
2040	1121.1	1637.4	1121.1		
2050	1513.3	2210.2	1513.3		
2060	2042.8	2893.5	2042.8		
2070	2757.4	4027.3	2757.4		
2080	3722.1	5436.2	3722.0		
2090	5024.4	7338.1	5024.4		
2100	6782.2	9905.4	6782.2		
Average % growth,					
1985-2000	1.5	1.7	5.8		
2000-2100	3.0	3.0	3.0		

Source: Brasseur and DeRudder (1986).

EXHIBIT 5-25

Time-Dependent Change in Ozone for CFC Growth and Coupled Perturbations (Brasseur and DeRudder 1-D Model)



Time-dependent changes in ozone as calculated by Brasseur and DeRudder (1986). Trace gas assumptions are shown in Exhibit 5-30 and may be summarized as:

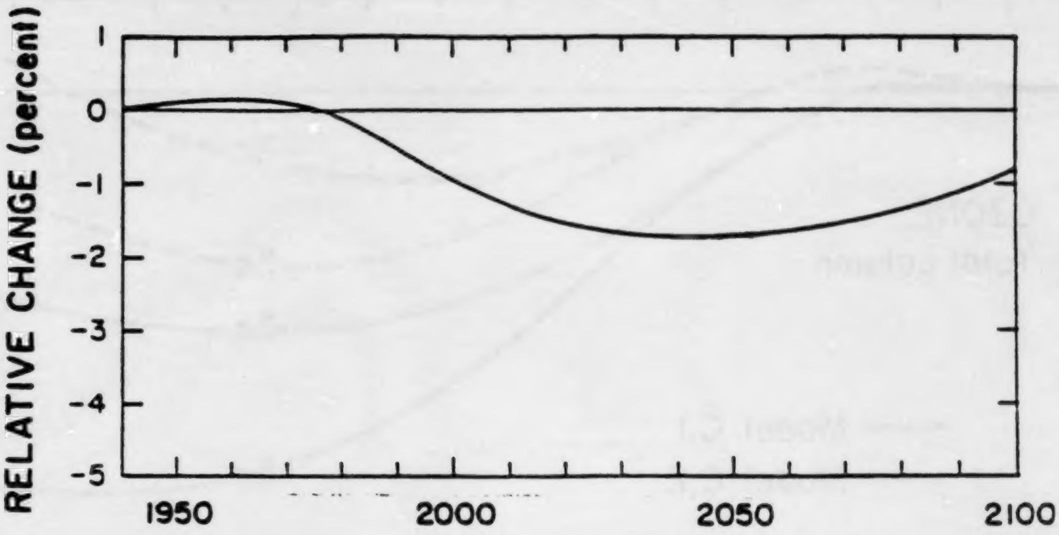
Compound	Average Growth Rate (% year)	
CFC-11 and CFC-12	1.5% to 2000, 3% from 2000 to 2100	(production)
CFC-113	5.8% to 2000, 3% from 2000 to 2100	(production)
CCL4	constant	(production)
CH3CCl3	constant	(production)
CH4	1.0	(concentrations)
N2O	0.25	(concentrations)
CO2	-0.50	(concentrations)
Halons	Not included	

Global ozone depletion increases to 5 percent by 2040 and to 30 percent by 2080.

Source: Brasseur and DeRudder (1986).

EXHIBIT 5-26

Time-Dependent Change in Ozone for Constant CFC Production and Growth in Other Trace Gases (Brasseur and DeRudder 1-D Model)



Time-dependent change in ozone as calculated by Brasseur and DeRudder, (1986) for constant CFC-11, CFC-12 and CFC-113 production at the 1985 level. Does not include Halons. Growth in other trace gases is:

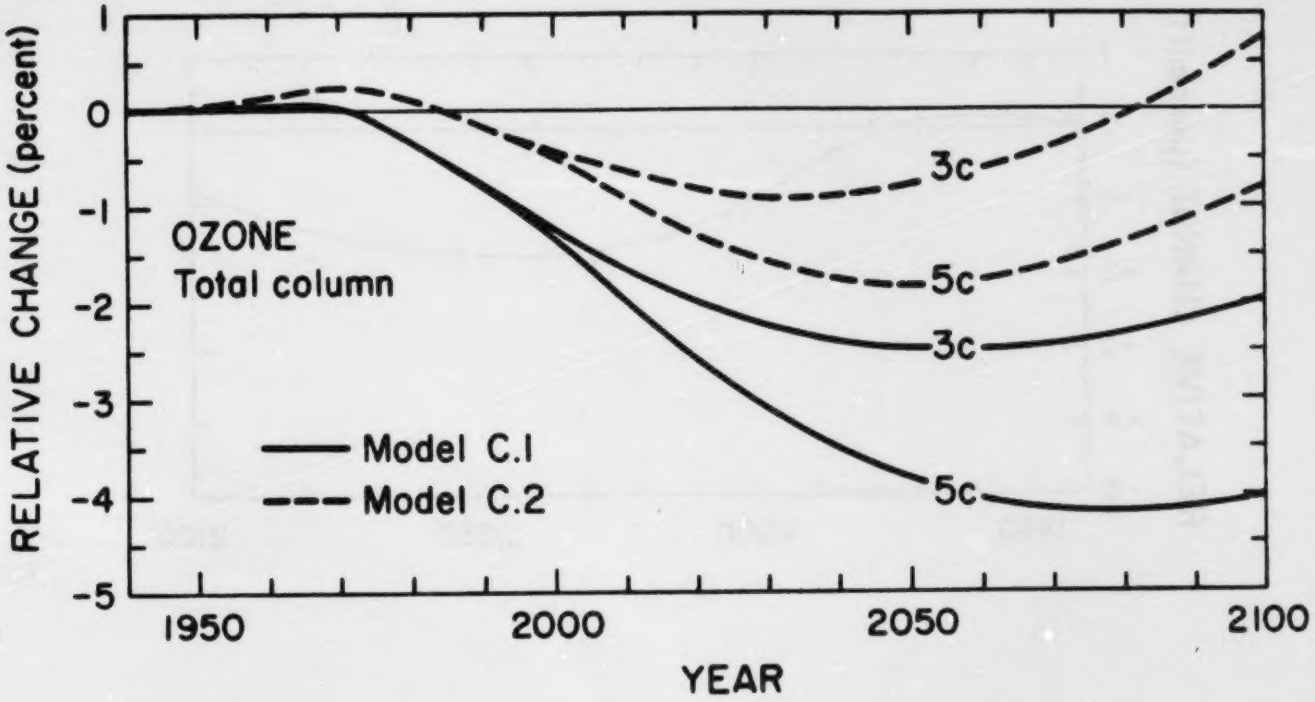
Compound	Growth Rate in Concentrations (%/year)
CH4	1.0
N2O	0.25
CO2	-0.5

Depletion increases to almost two percent before the effects of increasing CH4, N2O, and CO2 concentrations overwhelm the effects of increased chlorine.

Source: Brasseur and DeRudder (1986).

EXHIBIT 5-27

Sensitivity of 1-D Models to Representation of Radiative Processes (Brasseur and DeRudder 1-D Model)



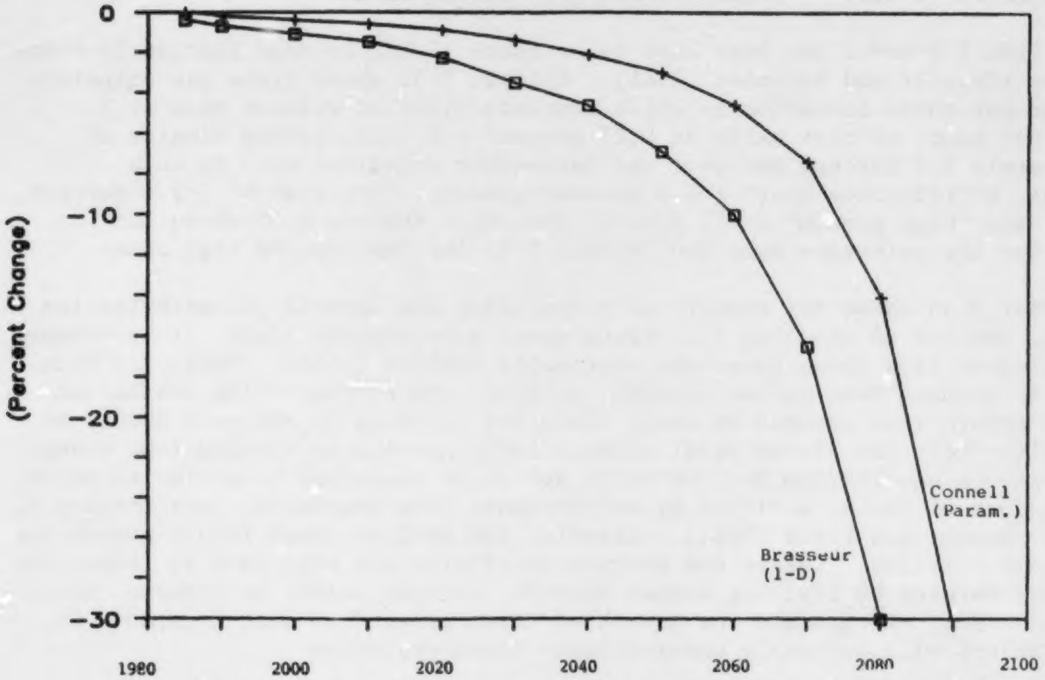
Time-dependent changes in ozone as calculated for two trace gas scenarios with two different model representations of radiative processes. Solid lines represent a treatment with radiative code, that is, run iteratively until radiative equilibrium conditions are reached in the stratosphere (above approximately 14 km). Below 14 km a convective adjustment is performed such that the lapse rate never exceeds -5.9 K/km. The dashed lines show the case where the radiative code has fixed equilibrium temperatures at the surface.

Scenario "3C" assumes constant production of CFC-11 and CFC-12 at 1985 levels. Scenario "5C" assumes that CFC-11 and CFC-12 production grows at 3 percent per year and is capped at a level of 1.5 times current production. In both scenarios it assumed that CFC-113 grows at 6 percent per year but is not allowed to exceed the production level of CFC-11. Does not include Halons.

Source: Brasseur and DeRudder (1986).

EXHIBIT 5-28

Model Comparison: Time-Dependent Change in Ozone for CFC Growth and Coupled Perturbations



Time-dependent change in ozone, as calculated by the 1-D model of Brasseur and DeRudder (1986) and Connell's parameterization of the LLNL 1-D model. Trace gas assumptions are shown in Exhibit 5-30 and may be summarized as:

Compound	Growth Rate (%/year)	
CFC-11 and CFC-12	1.5% to 2000, 3% from 2000 to 2100	(production)
CFC-113	1.0% to 2000, 3% from 2000 to 2100	(production)
CCl4	constant	(production)
CH3CCl3	constant	(production)
CH4	1.0	(concentrations)
N2O	0.25	(concentrations)
CO2	~0.50	(concentrations)
Halons	Not included	

Note that Connell's parameterization produces lower results than Brasseur's 1-D model.

Sources: Brasseur and DeRudder (1986); Connell (1986).

The time-dependent AER scenarios are shown in Exhibit 5-29, and the results in Exhibit 5-30. They are roughly consistent with Brasseur's runs, indicating that global average depletion over 1 percent will occur even if greenhouse gases are not limited, unless CFCs and other depleters do not grow in concentration beyond current levels.

The LLNL 1-D model has been used to estimate global average changes in ozone over time (Connell and Wuebbles, 1986). Exhibit 5-31 shows trace gas emissions over time for three scenarios in which concentrations of methane grow at 1 percent per year, nitrous oxide at 0.25 percent per year, carbon dioxide at approximately 0.6 percent per year and halocarbon emissions vary in each scenario: a "reference case" (~2.5 percent growth), "low growth" (~1.4 percent growth), and "high growth" (~4.1 percent growth). Exhibit 5-32 shows the results for the reference case and Exhibit 5-33 for the low and high cases.

Exhibit 5-34 shows the results of a run using the Connell parameterization in which, instead of assuming greenhouse gases grow without limit, it is assumed that emissions from these gases are eventually limited (Gibbs, 1986). In that run, it is assumed that carbon dioxide, methane, and nitrous oxide are halved from the growth rate assumed in other scenarios starting in the year 2000. As the results show, the limits still allow a large greenhouse warming (the change in temperature equilibrium for the earth for these scenarios is estimated using the equations of Lacis, modified by coefficients from Ramanathan [see Chapter 6] [Hoffman, Wells, and Titus 1986]). Clearly, assumptions about future greenhouse warming are critical. Unless one assumes no efforts are ever made to reduce the greenhouse warming by limiting carbon dioxide, nitrous oxide, or methane, model runs that merely extrapolate the growth of these gases from past increases in concentrations will seriously underestimate ozone depletion.

TIME-DEPENDENT PREDICTIONS FOR TWO-DIMENSIONAL MODELS WITH DIFFERENT SCENARIOS OF TRACE GASES

Isaksen and Stordal have conducted two sets of time-dependent runs using their two-dimensional model. Sze and Brasseur have also performed time-dependent 2-D runs. The two sets of Isaksen runs differ in one important respect. In one set of model runs, temperature feedback is not considered and carbon dioxide was implicitly assumed not to grow. In the second set of runs, however, the radiative cooling for rising carbon dioxide is considered using values for carbon dioxide cooling obtained from the Goddard Institute for Space Studies general circulation model. Sze's runs ignore the effects of carbon dioxide on stratospheric temperatures.

For the period 1960-1980, Isaksen used CFC release rates from **Cunnold et al. (1983a, CFC13), Cunnold et al. (1983b, CF2C12), Prinn et al. (1983b, CH3CC13) and Simmonds et al. (1983, CC14). The atmosphere was assumed to initially (1960) contain 0.6 ppb of CH3Cl and 0.1 ppb of CC14, resulting in a 1 ppb content of stratospheric chlorine. The CH3Cl surface flux needed to obtain the 1960 mixing ratio was kept constant in all the computations. For the CFC13, CF2C12 and CH3CC13, the integrations were started in 1960 with zero abundances and releases corresponding to amounts accumulated in the years prior to 1960, which is a reasonable assumption since the releases were small before 1960.** (Stordal and Isaksen, 1986)

EXHIBIT 5-29

Trace Gas Assumptions for Results in Exhibit 5-30
(AER 1-D Model, 1986)

	CH4*		CFC**	
SCENARIO	1960-2020	After 2020	1985-2008	After 2008
1A	1.0	1.0	No CFC Emission	
2A	1.0	1.0	Constant at 1984 Rates	
3A	1.0	1.0	3.0	Constant at 2008 rate
3B	1.0	0.5	3.0	Constant at 2008 rate
4A	1.0	1.0	3.0	Constant at 1984 rate
4B	1.0	0.5	3.0	Constant at 1984 rate

* Methane growth rate is in percent per year for the periods 1960-2020 and after year 2020.

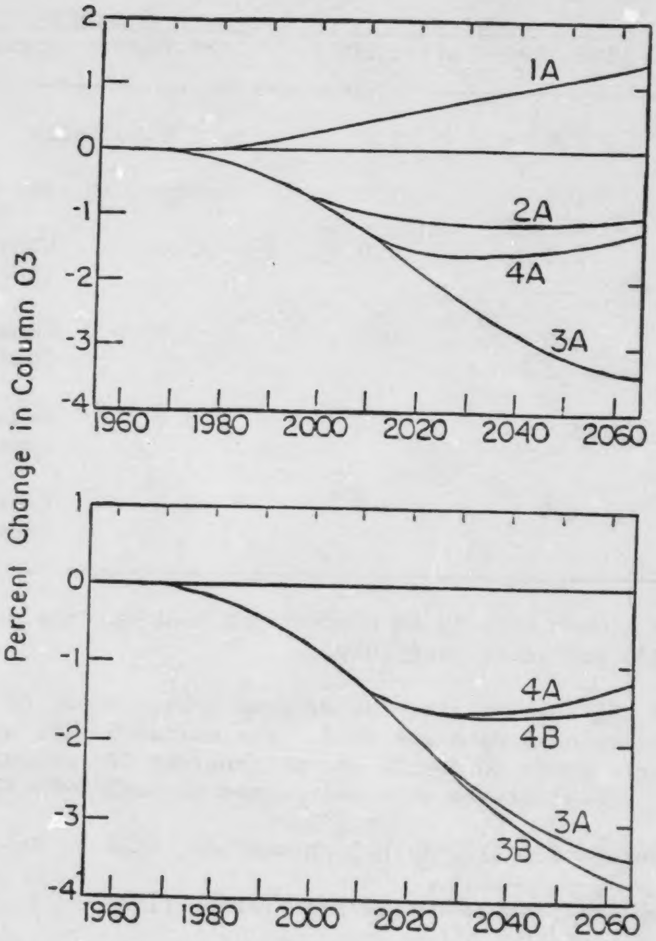
** Assumed CFC release rates after year 1985. Prior to 1985, historic release data are used. The emission rate at the year 2008 corresponds to double the present-day CFC production if 3 percent annual growth were maintained through 1985-2008.

Does not include CFC-113, methyl chloroform, CCL4 or Halons.

Source: Chemical Manufacturers Association (1986).

EXHIBIT 5-30

Time-Dependent Change in Ozone for Various Scenarios of Coupled Perturbations (AER 1-D Model)



Time-dependent change in ozone as calculated by the AER 1-D model for several scenarios of growth in trace gas emissions and concentrations, shown in Exhibit 5-29. The results indicate that global average depletion over one percent will occur if growth in CFCs and other potential ozone depleters continues.

Source: Chemical Manufacturers Association (1986).

EXHIBIT 5-31

Trace Gas Scenarios Tested in LLNL 1-D Model
(Emissions in millions of kg/year)

	CFC-11 ($CFCl_3$)			CFC-12 (CF_2Cl_2)			CFC-113 ($CF_2ClCFCl_2$)		HCFC-22 (CHF_2Cl)	
Year	Reference	Low	High	Reference	Low	High	High	Low	High	Low
									52	54
1985	325	324	594	449	446	527	102	102	84	71
1990	428	422	1184	528	519	722	142	142	122	89
1995	553	476	1486	625	573	1042	210	157	167	107
2000	717	522	2428	746	611	1406	277	180	221	127
2005	870	558	5456	870	647	1997	311	202	273	137
2010	1024	594	8485	995	683	2587	344	224	332	148
2015	1173	626	17422	1130	723	3483	378	245	394	155
2020	1322	657	26358	1266	763	4378	411	267	463	163
2025	1480	691	35841	1415	808	5219	445	289	541	170
2030	1637	725	45323	1564	853	6058	493	320	626	178
2035	1826	762	47666	1742	902	6499	540	351	715	187
2040	2006	798	50009	1919	951	6940	588	381	807	196
2045	2237	837	51790	2131	1004	7299	635	412	900	205
2050	2468	876	53570	2342	1058	7658	683	443	998	216
2055	2702	918	54795	2556	1118	7890	753	489	1097	226
2060	2937	960	56020	2770	1177	8122	823	534	1195	238
2065	3188	1006	57044	2998	1245	8278	893	580	1292	250
2070	3440	1053	58068	3226	1312	8434	963	625	1387	263
2075	3711	1104	69555	3472	1386	8547	1033	671	1495	276

EXHIBIT 5-31 (continued)

Trace Gas Scenarios Tested in LLNL 1-D Model
(Emissions in millions of kg/year)

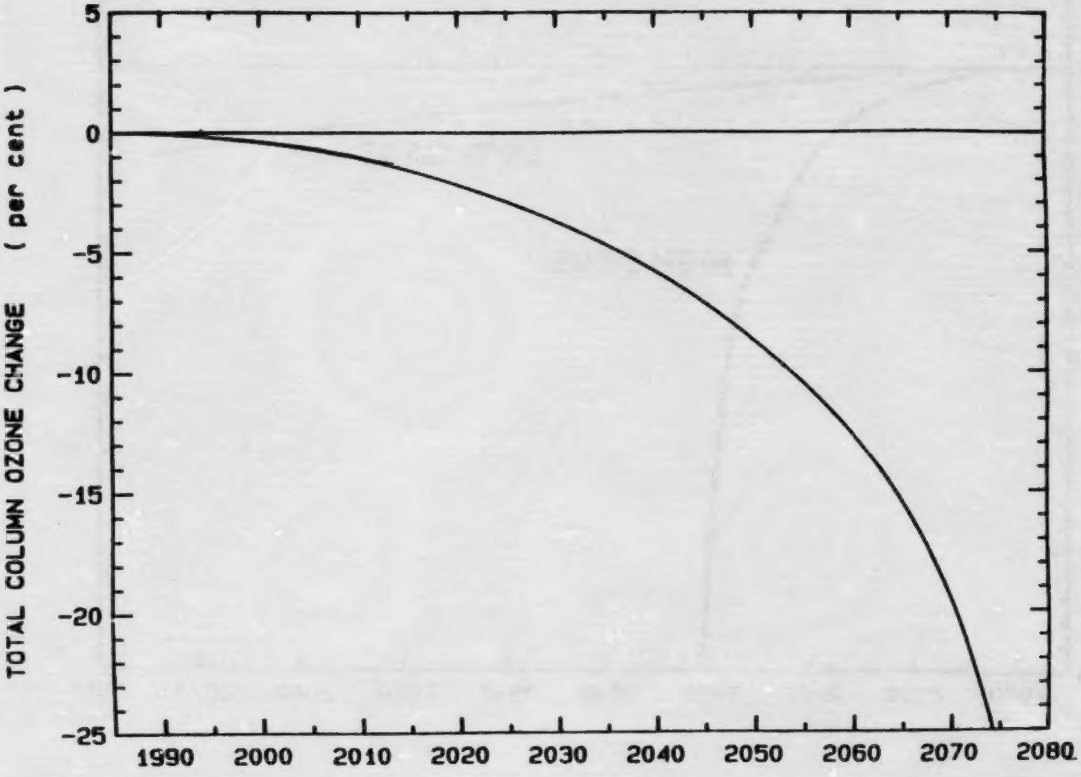
Year	CC14 10^6 Reference and High	CC14 10^6 Low	CH3CC13 (methyl chloroform) Reference, Low, and High	HALON 1301 (CF3Br) Reference, High	HALON 1301 (CF3Br) Low	HALON 1211 (CF2BrC1) Reference, High	HALON 1211 (CF2BrC1) Low
1985	153	131	510	2	1	0	0
1990	188	41	569	3	2	1	0
1995	206	45	634	4	2	1	0
2000	226	49	708	6	3	1	1
2005	250	54	793	9	4	1	1
2010	275	59	878	12	5	2	1
2015	300	64	963	16	7	3	2
2020	325	70	1049	19	9	4	2
2025	350	76	1135	22	11	5	2
2030	384	83	1256	25	12	5	2
2035	419	91	1377	29	14	6	3
2040	454	99	1499	32	16	7	3
2045	489	107	1621	36	18	8	4
2050	524	115	1743	39	20	9	4
2055	576	126	1922	43	21	9	4
2060	628	137	2101	47	23	10	5
2065	680	148	2280	51	25	11	5
2070	732	160	2459	55	27	12	6
2075	784	172	2638	59	29	13	7

Biogenic Trace Gases: CH4 concentrations at 1% per year, N20 at 0.25% per year, and CO2 at approximately 0.6% per year.

Source: Connell and Wuebbles (1986).

EXHIBIT 5-32

Time-Dependent, Globally Averaged Change in Ozone for Coupled Perturbations
(LLNL 1-D Model)
"Reference Case"

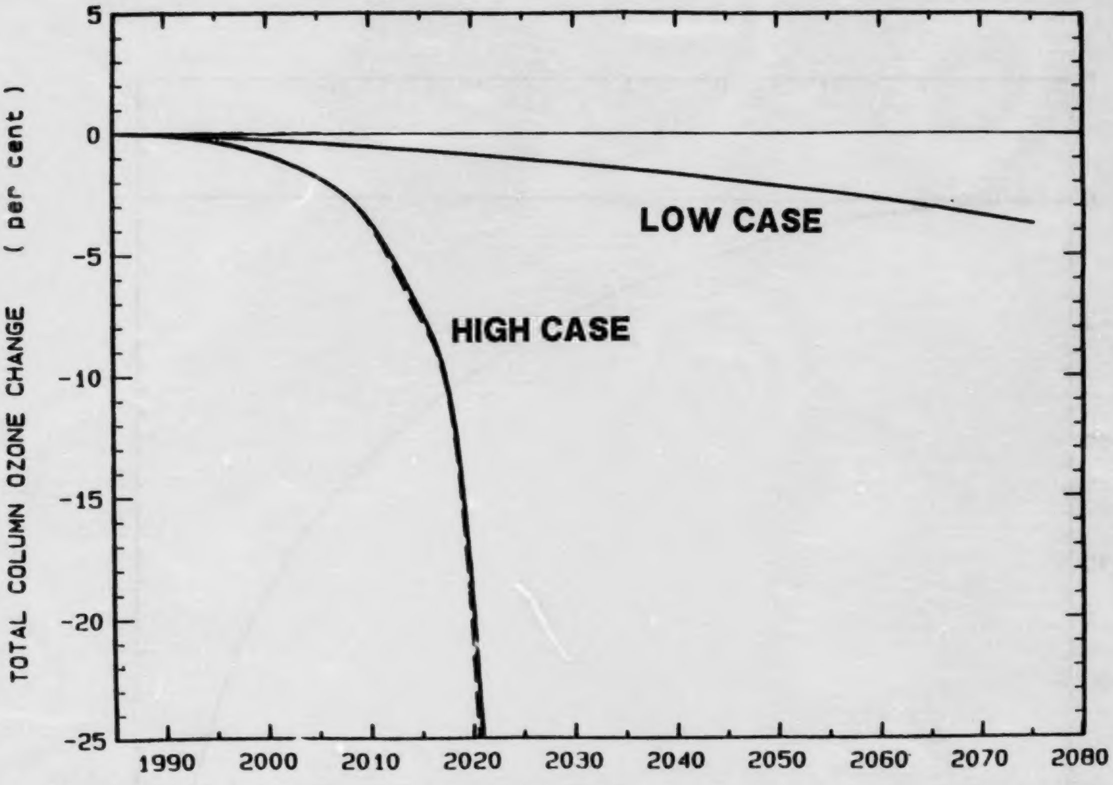


Total column ozone change for "reference case" scenario of trace gases: ~2.5 percent growth in CFC emissions, concentrations of CH4 at 1 percent, N2O at 0.25 percent, and carbon dioxide at ~0.6 percent.

Source: Connell and Wuebbles (1986).

EXHIBIT 5-33

Time-Dependent, Globally Averaged Change in Ozone for Coupled Perturbations (LLNL 1-D Model)



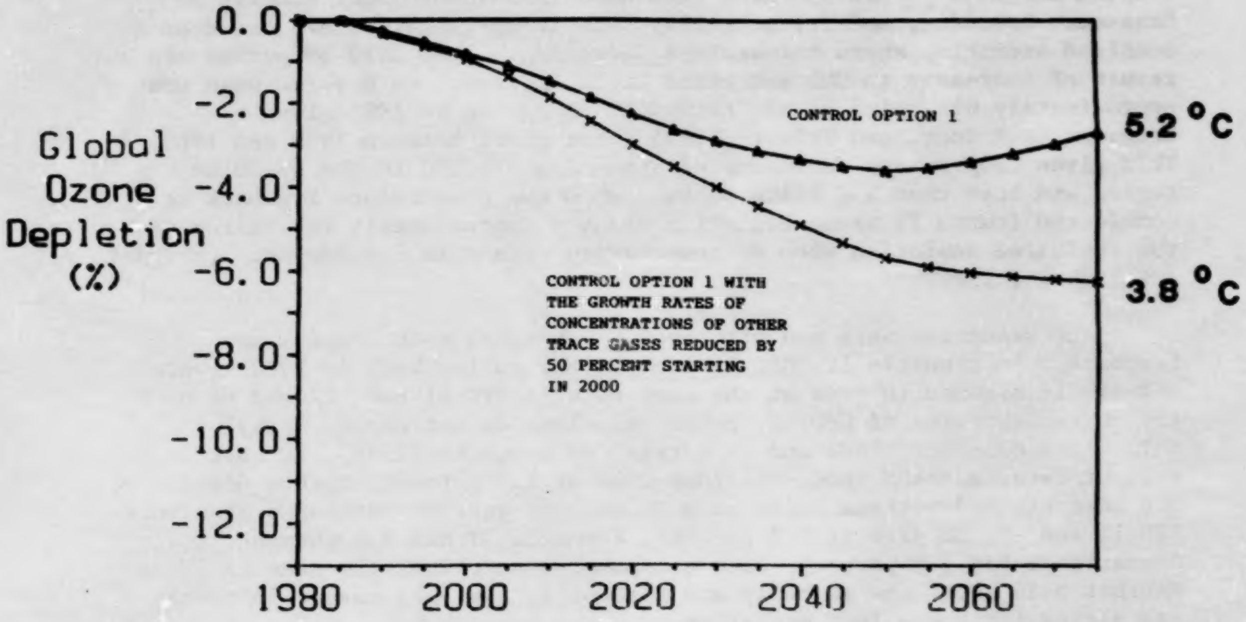
Total column ozone change for "low" and "high" scenarios of trace gases:

	Low	High	
CFCs	1.4	4.1	(emissions)
CH4	1.0	1.0	(concentrations)
N2O	0.25	0.25	(concentrations)
CO2	-0.6	-0.6	(concentrations)

Source: Connell and Wuebbles (1986).

EXHIBIT 5-34

Effect of Potential Greenhouse Gas Controls on Ozone Depletion (Results from 1-D Parameterization)



Source: Gibbs(1986). "Analysis of the Importance of Various Design Factors in Determining the Effectiveness of Control Strategy Options." UNEP Workshop

Change in global average ozone as calculated by a parameterized version of the LLNL 1-D model (see Connell, 1986). Control option 1 is:

CFCs	2.5%	(emissions) until CFCs double
CH4	1.0%	(concentrations)
N2O	0.25%	(concentrations)
CO2	-0.6%	(concentrations)

In "Half Trace Gas" curve, action is simulated in the year 2000 to cut the growth rates in half for concentrations of CH4, N2O, and CO2. The temperature equilibrium uses 3°C as the temperature sensitivity for doubled CO2. Actual equilibrium temperatures could be plus or minus 50 percent.

Source: Gibbs (1986).

In looking at the time period in which actual measurements exist, the IS model performs well in comparison to Umkehr measurements (Exhibit 5-35). **Estimates with temperature feedback (curve 1) give upper stratospheric ozone depletion larger than what is deduced from Umkehr observations. We have, however, also done one model study where we included temperature changes between 1979 and 1980. The stratospheric temperature decrease adapted for this period is taken from one-dimensional model studies by Brasseur, DeRudder, and Tricot (1985). Their calculations are based on a combined scenario, where temperature decreases in the 1970-80 period are a result of increases in CO2 and other trace species. We have assumed that approximately one-third of the estimated change up to 1983 given by Brasseur, DeRudder, and Tricot (1985) takes place between 1970 and 1980. This gives temperature decreases of approximately 1°C in the 45-50 km region and less than 1°C below 35 km. When the temperature feedback is considered (curve 2) ozone depletion becomes approximately two-thirds of the estimated depletion when no temperature effect is considered.** (Stordal and Isaksen, 1986)

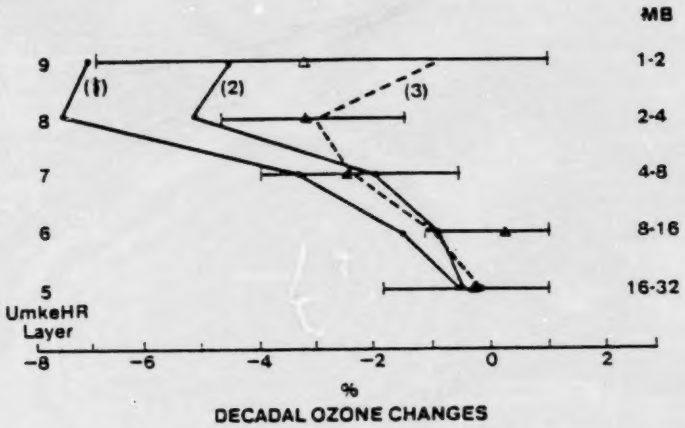
Four scenarios were run with the IS 2-D model with temperature feedback. In scenario 1T, CFC-11 and -12 are rolled back to 1980 levels, CFC-113 is assumed to grow at the same rate as CFC-11 and -12 and to have the characteristics of CFC-12, halon emissions do not occur, methyl chloroform concentrations and CCl_4 rise, as in Quinn (1985), at about a 2 percent rate, methane concentrations rise at 1.0 percent, carbon dioxide at 0.6 percent, and nitrous oxide at 0.25 percent yearly. Scenario 2T allows CFC-11 and -12 to grow at 1.2 percent, Scenario 3T has 3.0 percent, and Scenario 4T has 3.8 percent, with all other assumptions the same as 1T. Exhibit 5-36 shows the globally and seasonally averaged change in ozone calculated for these four scenarios.

Scenarios 1WT, 2WT, 3WT, 4WT are scenarios without temperature feedback, assuming essentially that carbon dioxide does not grow. These scenarios may be thought of as the case in which greenhouse warming is limited, although it is unlikely that carbon dioxide would be reduced to no growth and nitrous oxide and methane allowed to grow. The main value of these scenarios is that they demonstrate the additional susceptibility of the stratosphere to depletion if greenhouse warming is limited by reducing carbon dioxide or other greenhouse gases. Of course, the effects of limiting nitrous oxide or methane would be quantitatively somewhat different than limiting carbon dioxide, but would still exacerbate depletion at some latitudes. Exhibit 5-37 shows the results for global averages.

The results of the various scenarios that include the stratospheric cooling (temperature feedback) associated with rising carbon dioxide are included in Exhibits 5-36, 5-38, 5-39, 5-40, and 5-41. Several important results are clear from these runs. If CFCs grow at 3.8 percent, while Halons are eliminated, and methane grows at 1 percent and nitrous oxide at 0.25 percent, depletion will exceed 4 percent (from a 1985 base) at 50°N before the year 2010. Since near-term growth estimates do not preclude growth at 3.8 percent (see Chapter 3), these results are particularly important. For growth of 3.0 percent for CFC-11 and -12 (with all other assumptions about limiting depleters and allowing greenhouse gases to grow), depletion will exceed 4 percent at 60°N by 2015. For

EXHIBIT 5-35

Calculated Ozone Depletion for 1970 to 1980 vs. Umkehr Measurements

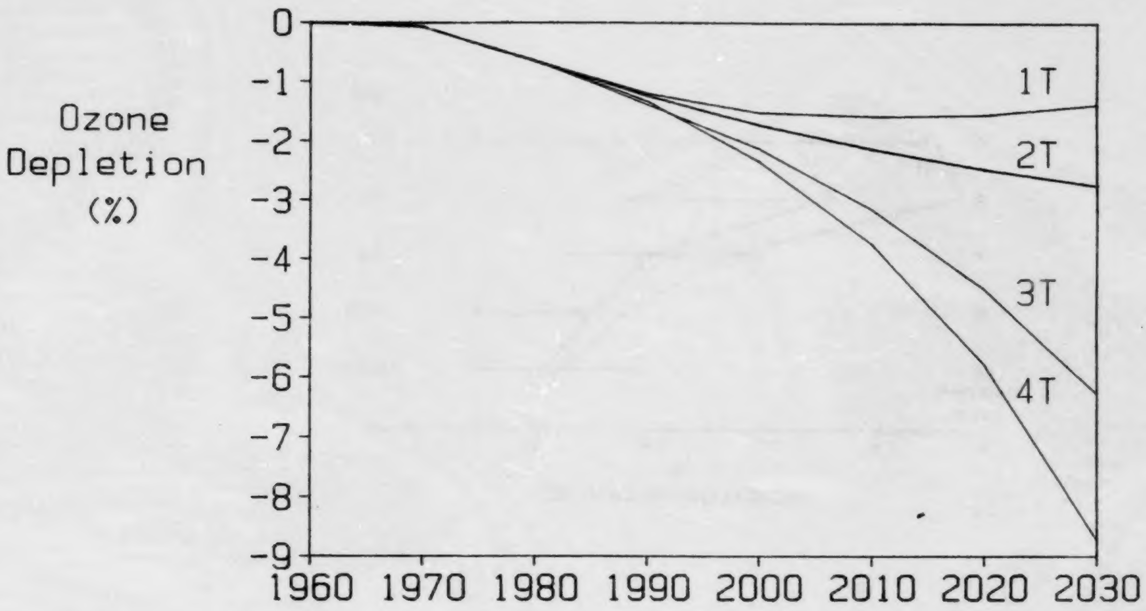


"Calculated ozone depletion between 1970 and 1980 without (curve 1) and with (curve 2) temperature changes from radiatively active gases in the stratosphere. The adapted temperature change is taken from a 1-D model study by Brasseur, DeRudder, and Tricot (1985). Estimated global trends (Reinsel et al. 1983; Reinsel et al. 1984) are based on Umkehr data (triangles with error bars). A one-dimensional model calculation by Wuebbles, Luther, and Penner (1983) is included (3)."

Source: Stordal and Isaksen (1986).

EXHIBIT 5-36

Time-Dependent Globally and Seasonally Averaged Changes in Ozone for Coupled Perturbations (IS 2-D Model)



For four scenarios of trace gas growth results show:

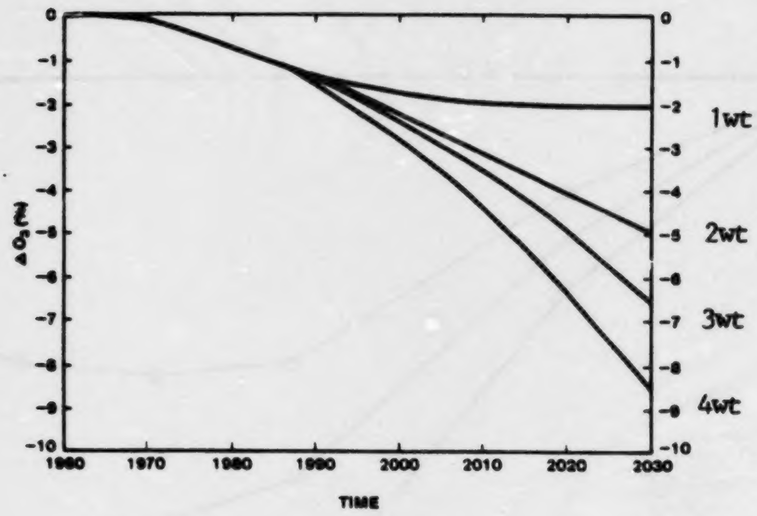
Scenario	CFC-11 and CFC-12
1T	1980 levels
2T	1.2% growth
3T	3.0% growth
4T	3.8% growth

Assumptions for other trace gases are the same in each scenario: emissions of CFC-113 parallel CFC-12 and are treated identically, constant CCl4 and CH3CCl3 emissions, zero emissions of halons, 1 percent growth per year in CH4, and 0.25 percent growth per year in N2O. CO2 concentrations grow at 0.5 percent. Temperature Feedback considered in model.

Source: Isaksen, personal communication.

EXHIBIT 5-37

Time-Dependent Globally and Seasonally Averaged Changes in Ozone for Coupled Perturbations (IS 2-D Model)



TRACE GAS ASSUMPTIONS

CFC-11 and CFC-12

Scenario 1T: Constant emissions at 1986 levels

Scenario 2T: CFC-11 assumed to grow at an 'average' annual rate of 1.4% (5% from 1980 to 1990; 1.1% from 1990 to 2000; 1.0% from 2000 to 2040, and 0.9% from 2040 to 2075). This scenario is taken from Quinn et al., (1986), Scenario II "Slow Growth"

Scenario 3T: Growth of 3% per year.

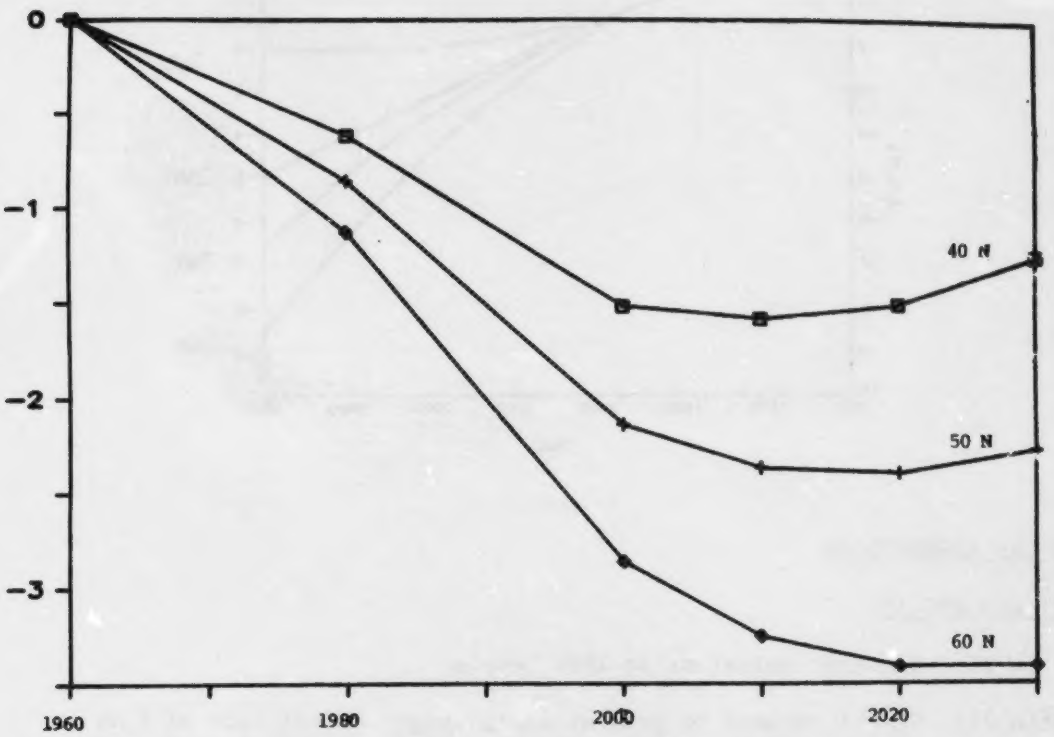
Scenario 4T: CFC-11 and CFC-12 increase at approximately 3.5% per year and 5% per year until 2000, after which growth gradually declines to 2% per year by 2075. This scenario is the average of Scenario VI "Later Market Maturation" and Scenario VII "New Markets" from Quinn et al., (1986).

Assumptions for other trace gases are the same in each scenario: emissions of CFC-113 grow at the same rate as CFC-12 and are treated identically, constant CCl4 and CH3CCl3 emissions, zero emissions of halons, 1 percent growth per year in CH4 and 0.25 percent growth per year in N2O. CO2 concentrations are held constant. Temperature Feedback not considered in model.

Source: Isaksen (1986).

EXHIBIT 5-38

Time-Dependent Seasonally Averaged Change in Ozone for 1980 CFC Emissions and Coupled Perturbations (IS 2-D Model)

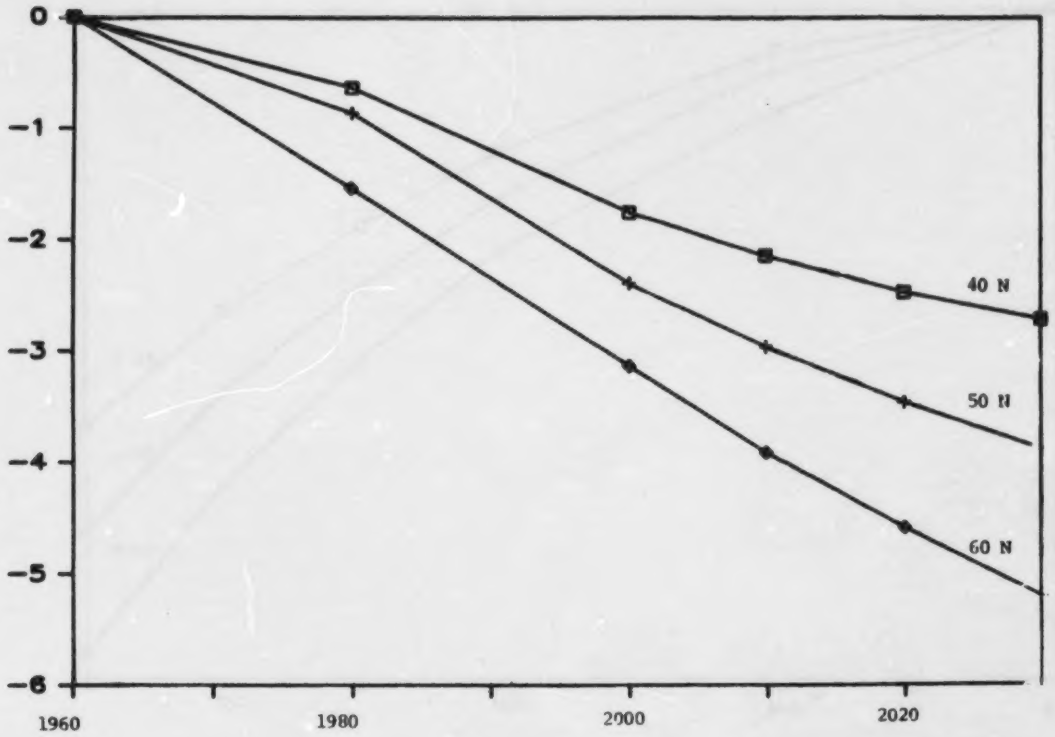


Results shown from constant CFC emissions at the 1980 level (approximately 10 percent less than current emissions); CH4 concentrations at 1 percent per year, N2O concentrations at 0.25 percent per year, and CO2 concentrations at approximately 0.5 percent per year. Methyl chloroform and CCl4 are essentially capped; halons eliminated. Changes shown for 40°N, 50°N, and 60°N. Temperature feedback considered in model.

Source: Isaksen (personal communication)

EXHIBIT 5-39

Time-Dependent Seasonally Averaged Change in Ozone for 1.2% Growth in CFC Emissions and Coupled Perturbations (IS 2-D Model)

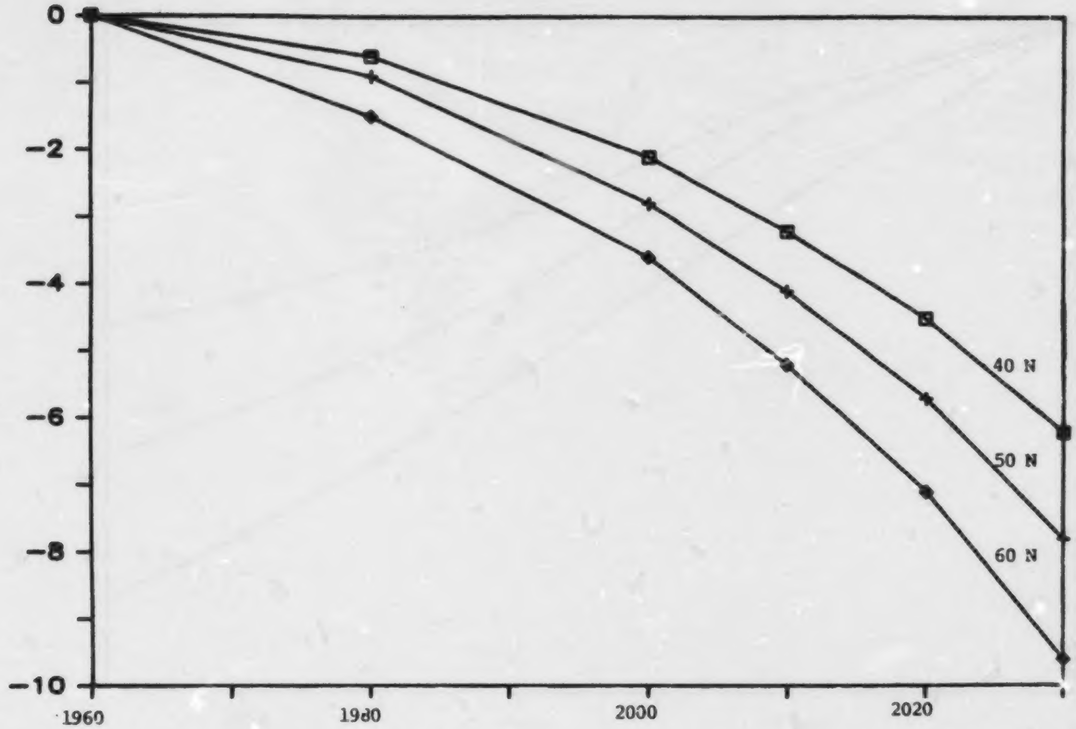


Results shown for 1.2 percent growth per year in CFC emissions, 1 percent growth in CH4 concentrations, 0.25 percent growth in N2O concentrations, and approximately 0.5 percent growth in CO2 concentrations. Methyl chloroform and CCl4 are essentially capped; halons eliminated. Changes shown for 40°N, 50°N, and 60°N. Temperature feedback considered in model.

Source: Isaksen (personal communication)

EXHIBIT 5-40

Time-Dependent Seasonally Averaged Change in Ozone for 3% Growth in CFC Emissions and Coupled Perturbations (IS 2-D Model)

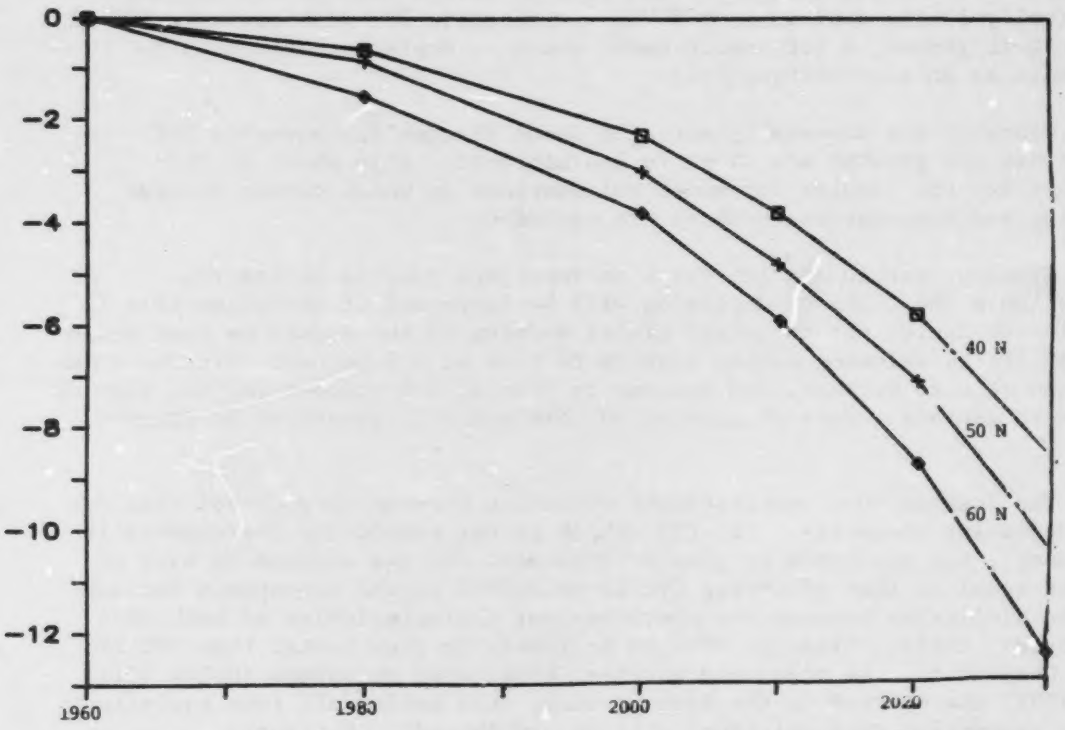


Results shown for 3 percent growth per year in CFC emissions, 1 percent growth in CH4 concentrations, 0.25 percent growth in N2O concentrations, and approximately 0.5 percent growth in CO2 concentrations. Changes shown for 40°N, 50°N, and 60°N. Temperature feedback considered in model.

Source: Isaksen (personal communication)

EXHIBIT 5-41

Time-Dependent Seasonally Averaged Change in Ozone for 3.8% Growth in CFC Emissions and Coupled Perturbations (IS 2-D Model)



Results shown for 3.8 percent growth per year in CFC emissions; 1 percent growth in CH4 concentrations; 0.25 percent growth in N2O concentrations, and approximately 0.5 percent growth in CO2 concentrations. Changes shown for 40^{o}N, 50^{o}N, and 60^{o}N. Temperature feedback considered in model.

Source: Isaksen (personal communication)

CFC-11 and -12 growth of 1.20 percent (and other assumptions limiting depleters and allowing greenhouse gas growth), 2 percent depletion will be exceeded at 50°N in 2015. Even if CFC-11 and -12 emissions are reduced 10 percent to 1980 levels (with other depleters limited and greenhouse gases growing), 1 percent depletion will be reached at 50°N by 2015, although the ozone layer would cover if greenhouse gases grow thereafter.

Examining the shape of the depletion curves is also instructive. In Scenario 1T, the rollback case, the rise of carbon dioxide and methane eventually limits depletion to 50°N. In scenario 3T, with moderate CFC-11 and CFC-12 growth, a turnaround never comes -- depletion continues to increase at an accelerating rate.

Globally and seasonally averaged ozone changes for scenario 3WT (moderate CFC growth) are shown in Exhibit 5-42. Also shown in this exhibit are the results for model calculations in which carbon dioxide cooling and temperature feedback are excluded.

Clearly, carbon dioxide plays an important role in countering depletion. The risks of depletion will be increased if decisionmakers in the future decide not to accept global warming of the magnitude that would be implied by allowing carbon dioxide to rise at 0.6 percent, nitrous oxide to rise at 0.25 percent, and methane to rise at 1.0 percent for the rest of the next century. More discussion on this point is presented in Chapter 18.

The Isaksen runs underestimate depletion because they do not consider all depleting chemicals. CFC-113, which is not explicitly represented in the model, was predicted to grow at 3 percent and was assumed to have an effect equal to that of adding CFC-12 emissions to the atmosphere because of the similarity between the photochemical characteristics of both CFCs (NASA/IPC, 1985). Clearly, CFC-113 is likely to grow faster than CFC-12 (see Chapter 3). As mentioned earlier, brominated compounds (Halon 1211 and 1301) are omitted in the Isaksen runs, thus making all runs equivalent to an assumption that emissions will be prohibited. (Currently, concentrations of Halon-1211 are growing at 23 percent (Khalil and Rasmussen, 1985). If bromine compounds grow at current or faster rates, depletion would be greater than predicted by these model runs (see earlier discussion on bromine).

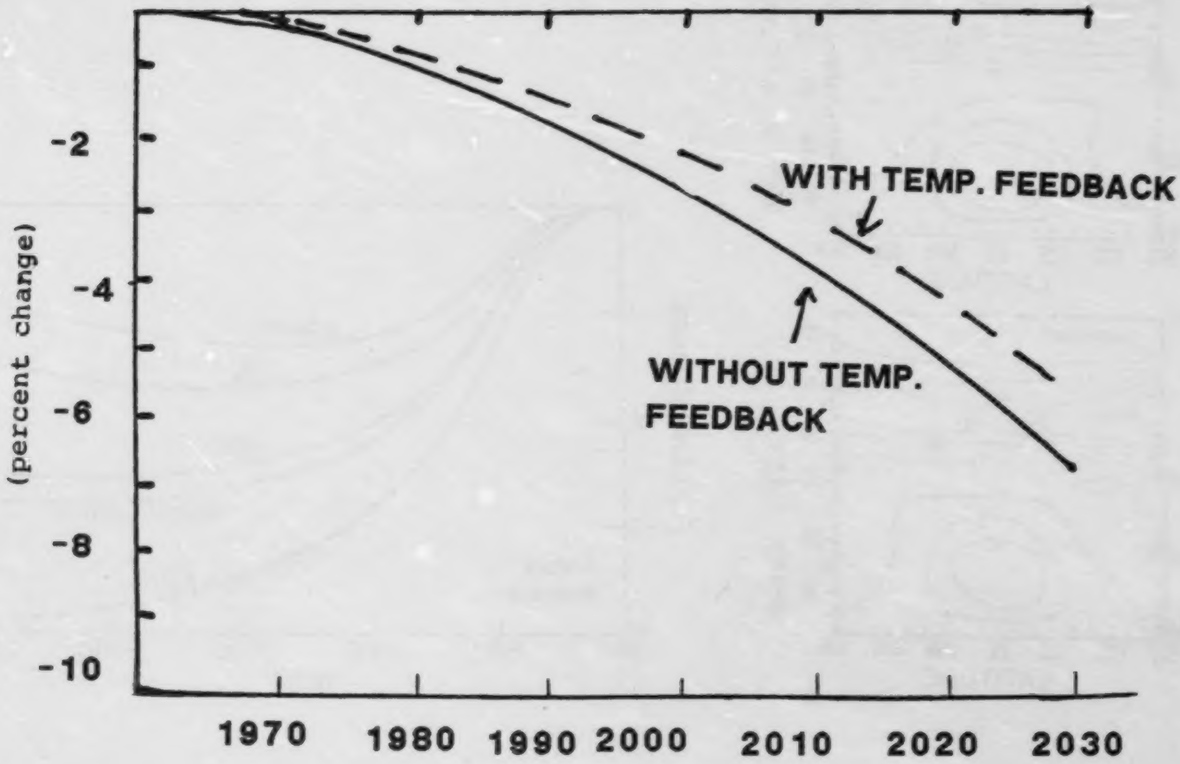
Sze's time-dependent simulations show results quite similar to Isaksen's, although latitudinal gradients and seasonality are somewhat different (Exhibit 5-43) (Sze, 1987). Brasseur's time-dependent 2-D runs are also quite similar (Brasseur, personal communication).

A Comparison of Results of One-Dimensional and Two-Dimensional Models

One-dimensional and two-dimensional models differ in their treatment of transport. One-dimensional (1-D) models, at best, project average global depletion. Two-dimensional (2-D) models project depletion by latitudes, which, of course, can be averaged together to estimate average global depletion. Exhibit 5-44 shows the averaged global depletion results

EXHIBIT 5-42

Temperature Feedback Experiment:
Time-Dependent, Globally and Seasonally Averaged Change
in Ozone for 3% Growth in CFC Emissions and Coupled Perturbations
(IS 2-D Model)

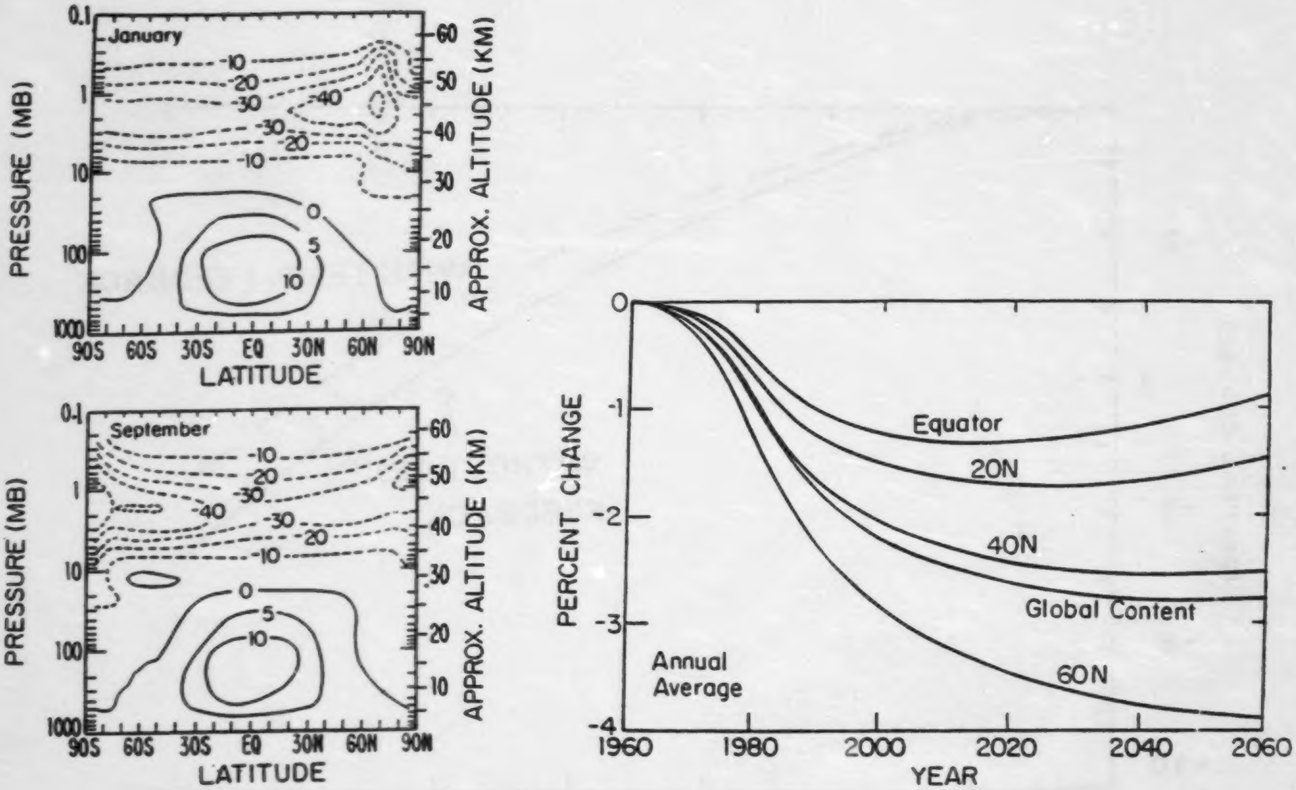


Results shown are for globally and seasonally average depletion for model experiment with and without temperature feedback from CO2 cooling.

Source: Isaksen (1986)

EXHIBIT 5-43a

Two-Dimensional, Time-Dependent Simulation for Constant CFC Emissions (AER 2-D Model)

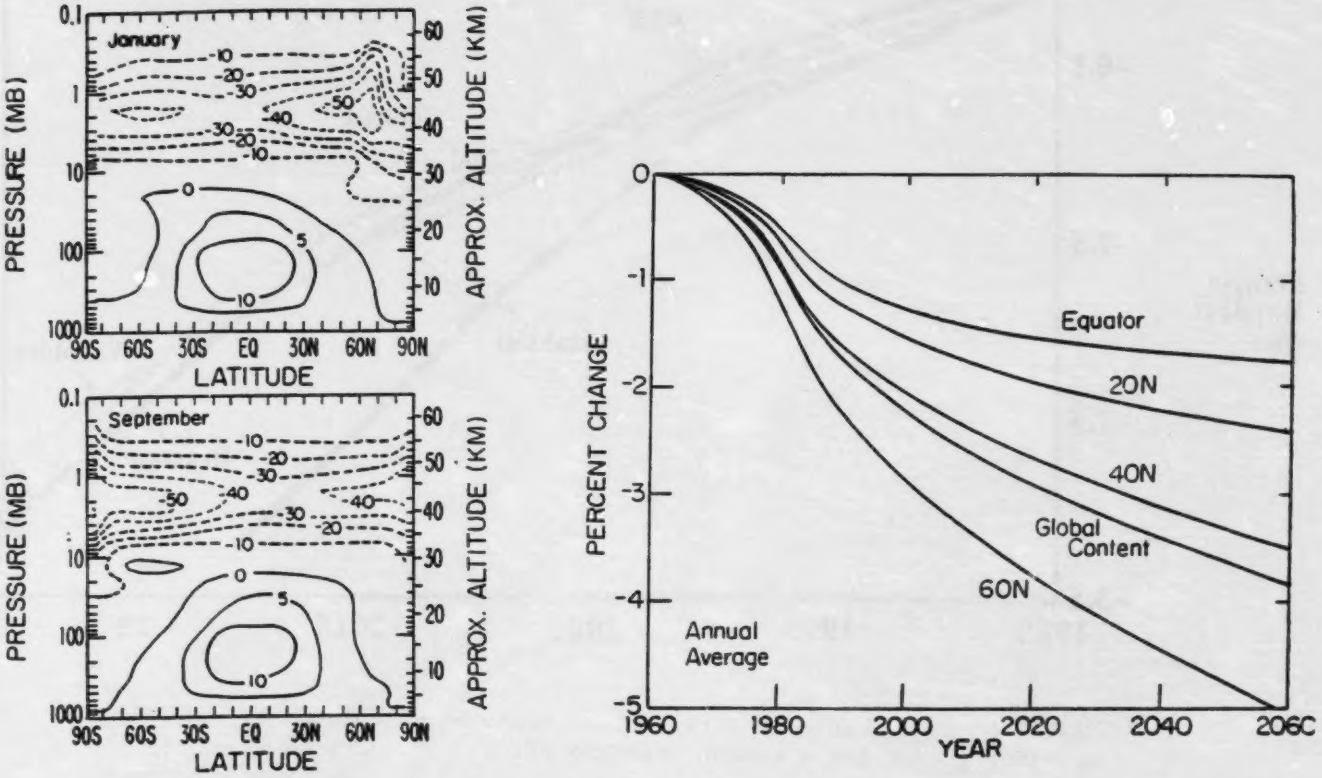


Calculated percent changes in ozone from 1960 to 2060 for constant CFC-11 and CFC-12 emissions and annual increases in CH4 and N2O concentrations of 1 percent and 0.25 percent, respectively. Model does not include CFC-113 or Halons, and assumes constant emissions of CCl4 and methyl chloroform.

Source: Sze, Ko and Weisenstein, 1986.

EXHIBIT 5-43b

Two-Dimensional, Time-Dependent Simulation for CFC Growth of 62 Percent Per Year (AER 2-D Model)

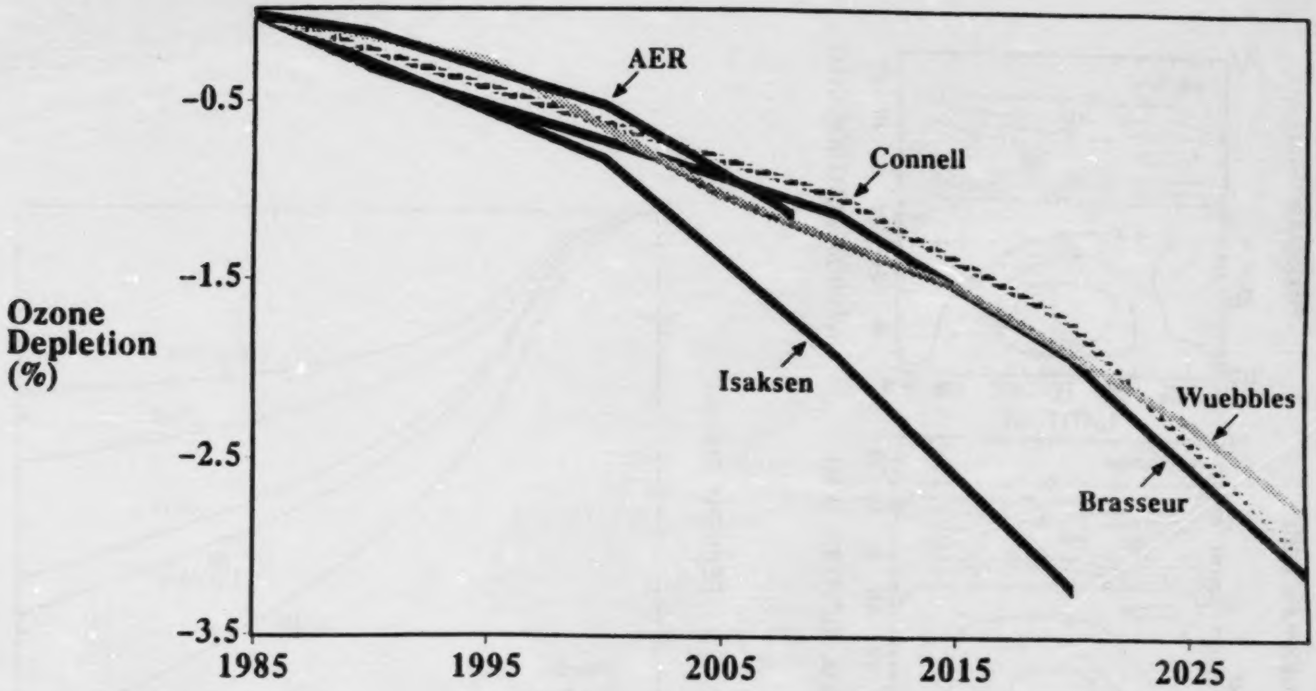


Calculated percent changes in ozone from 1960 to 2060 for projected 1.2 percent per year growth in emissions of CFC-11 and CFC-12, and annual increases in CH4 and N2O concentrations of 1 percent and 0.25 percent, respectively. Model does not include CFC-113 or Halons, and assumes constant emissions of CCl4 and methyl chloroform.

Source: Sze, Ko and Weisenstein, 1986.

EXHIBIT 5-44

Model Comparison for Coupled Perturbation Scenario



Global average change in total column ozone as calculated by several modeling groups for a common scenario of:

Compound	Growth Rate (% per year)
CFCs	3.0 (emissions)
CH4	1.0 (concentrations)
N2O	0.25 (concentrations)
CO2	-0.60 (concentrations)

Results shown for 2-D models of Isaksen and AER, 1-D models of Brasseur and Wuebbles, and Connell's parameterization of the LLNL 1-D model.

Source: Chemical Manufacturers Association (1986); World Meteorological Organization (1986); Connell (1986); Brasseur and DeRudder (1986); and Isaksen and Stordal (1986).

of Isaksen's and AER's 2-D models, Brasseur's 1-D model, and the Connell parameterization of the Lawrence Livermore 1-D model for very similar scenarios. The outcomes are relatively similar, indicating that the 1-D models and Isaksen's 2-D models do not differ in their fundamental projections for global results, and that Isaksen's model distributes depletion in a manner consistent with total global depletion from 1-D projections. The higher estimate from Isaksen's 2-D model is to be expected. In model comparisons done in the World Meteorological Organization (1986) assessment, the 2-D model of AER exhibited similar behavior to Isaksen's. The global average for AER's 1-D model, with exactly the same chemistry and an almost identical perturbation study, was 20 percent higher. While much remains to be learned about 2-D models, it is clear that they offer more information for monitoring, for validation (and invalidation), and for impact analyses than do 1-D models. The World Meteorological Organization (1986) report stated **"In summary, while 1-D models remain useful assessment tools for assessment, it is becoming clear that 2-D models provide a much more detailed picture of atmospheric response to perturbations.**

MODELS FAIL TO REPRESENT ALL PROCESSES THAT GOVERN STRATOSPHERIC CHANGE IN A COMPLETE AND ACCURATE MANNER

Current models fail to represent all the processes that will influence stratospheric change in either a complete or an accurate manner. While the models can reproduce many of the measurements that describe today's atmosphere, they fail to reproduce some observations very accurately. This, by itself, lowers our confidence in current model predictions, suggesting the need for careful sensitivity testing for various uncertainties and assumptions. In addition, theory suggests that models do not describe all processes in a completely accurate manner, suggesting the possibility that missing factors or simplified processes could undermine the accuracy of model projections.

The Nature of Model Validation for Geophysical Systems

In many science disciplines, the predictive power of theories and models can be confirmed by doing and redoing experiments. In this way experimenters can gain confidence by actually manipulating the system under study. For geophysical systems, this approach generally cannot be taken -- there is no experimental earth on which to conduct tests. Thus modelers attempt to validate their models by comparing them to the actual atmosphere. Such tests impose strong restrictions on models in the sense that there are many variables to be predicted, and fixing one aspect of a model's deficiencies often results in the emergence of a new deficiency. Even if a model reproduces the current world with complete fidelity, however, it may have substantial problems. There may be several models that reproduce existing conditions, yet projections of change from each could diverge. Models that 'fit well' may lack adequate power to predict the effects of perturbations if factors are missing from the model that are not critical in describing current conditions, but will be critical in describing future conditions. There always exists the possibility that some factor is missing, that some relationship that now holds will be invalid under future conditions. Without an experimental earth to use for model validation, it will always be impossible to eliminate that possibility.

Nevertheless, there are mechanisms for testing models and their robustness. Past assessments have reported changes in the prediction of ozone depletion (Exhibit 5-45) for the same scenarios. At first glance, these changes, in themselves, might be taken to reduce our confidence in the models. An examination of the cause of those changes, however, reveals that most occurred primarily as a product of new estimates in rate constants or cross sections from the laboratory. While it was impossible for laboratory kineticists to predict the changes that occurred in their laboratory estimates, kineticists certainly were not surprised that changes occurred, nor that they had implications on model outputs. Even today, after enormous improvements in laboratory procedures, uncertainty about kinetics and cross sections still exist. Clearly then, to avoid surprise in changes in the estimates of depletion in the future, we must examine a range of rate constants and cross sections to determine the extent to which model results depend on a unique set of inputs. Furthermore, it is instructive to consider the fact that chlorine increases constant with steady state for CFC has always produced depletion.

Another source of uncertainty that needs to be considered is transport. Chemical interactions may be described quite well by models, but if molecules do not move to areas to which they are expected to move, the outcome of models may be inaccurate.

To address these concerns, this section considers these three questions:

(1) How well do models reproduce the current atmosphere?

(2) How dependent are model predictions on a narrow range of kinetics and cross sections?

(3) How dependent are models on a single formulation of transport?

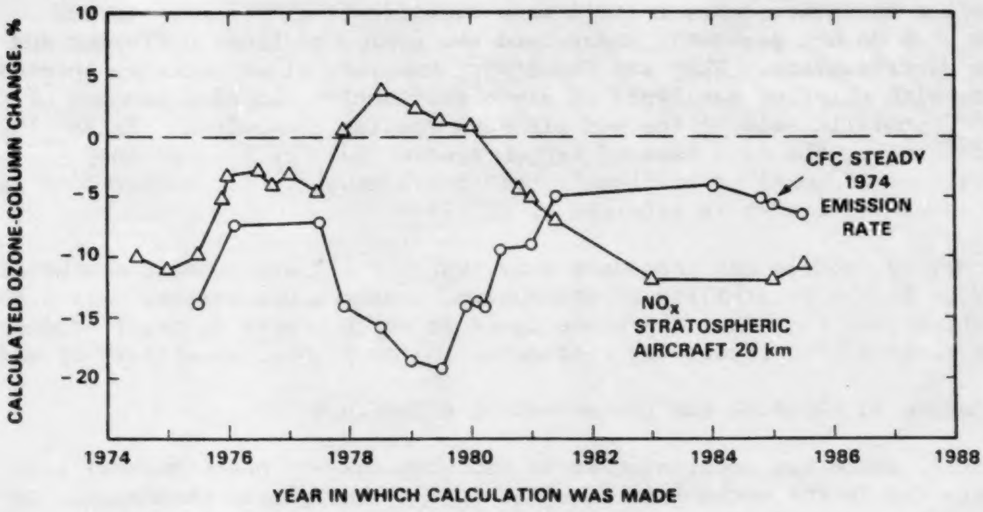
By answering these questions, it should be possible to establish a range of concern that should govern judgments about model reliability.

Agreements and Deficiencies In Model Representations of the Current Atmosphere

The extent to which models reproduce observed concentrations will have a bearing on the confidence we place in them. There are a few discrepancies between model predictions and the observed atmosphere, which lowers our confidence in the predictions of one- and two-dimensional models. **One** discrepancy **is that there is an inconsistency between modelled (using both one- and two-dimensional models) and measured (by both ground-based and satellite instrumentation) ozone abundances above 35 km by as much as 30-50%.** [For some], **it is particularly troubling that this problem occurs in an altitude region in which the ozone concentrations are photochemically controlled.** [Others feel that because this is a region with low ozone, the discrepancy is not that important.] **Furthermore, if the observed ozone concentrations are used in**

EXHIBIT 5-45

Calculated Ozone -- Column Change to Steady-State for Two Standard Assumed Perturbations



Calculations made at LLNL over 11 years showing changes in 1-D model results for two standard scenarios. Calculations used the then current photochemical parameters, eddy diffusion functions, and boundary conditions.

Source: World Meteorological Organization (1986).

radiative models of the upper stratosphere, the predicted temperatures are higher than measured. Another problem is that there are considerable differences in the distribution of odd nitrogen species that are computed by the models of different groups ([Exhibit 5-46]). This is true for both one- and two-dimensional models. This disagreement is understandable for the two-dimensional models given the differences in their formulations of transport, but is very disturbing for the one-dimensional models in which these differences cannot be attributed to differences in transport. One source for these differences in odd nitrogen distributions are the differing treatments for the penetration of solar radiation in the Schumann-Runge bands. However, models with similar radiation schemes still show significant differences in odd nitrogen. We do not presently understand the source of these different odd nitrogen distributions. They are important, however, since nitrogen species interfere with chlorine catalysis of ozone destruction and also because of the important catalytic role of the odd nitrogen species themselves. (NASA, 1986) Except for ozone, the data base of oxygen species is very limited and, therefore, not adequate to critically test these models. For comparisons with other species the reader is referred to WMO 1986.

In summary, models can reproduce many, but not all atmospheric measurements. Uncertainty in the reliability of atmospheric measurements hampers this effort. Nevertheless, the fact that there are cases in which models do not reproduce apparent observations lowers our confidence in the predictive ability of models.

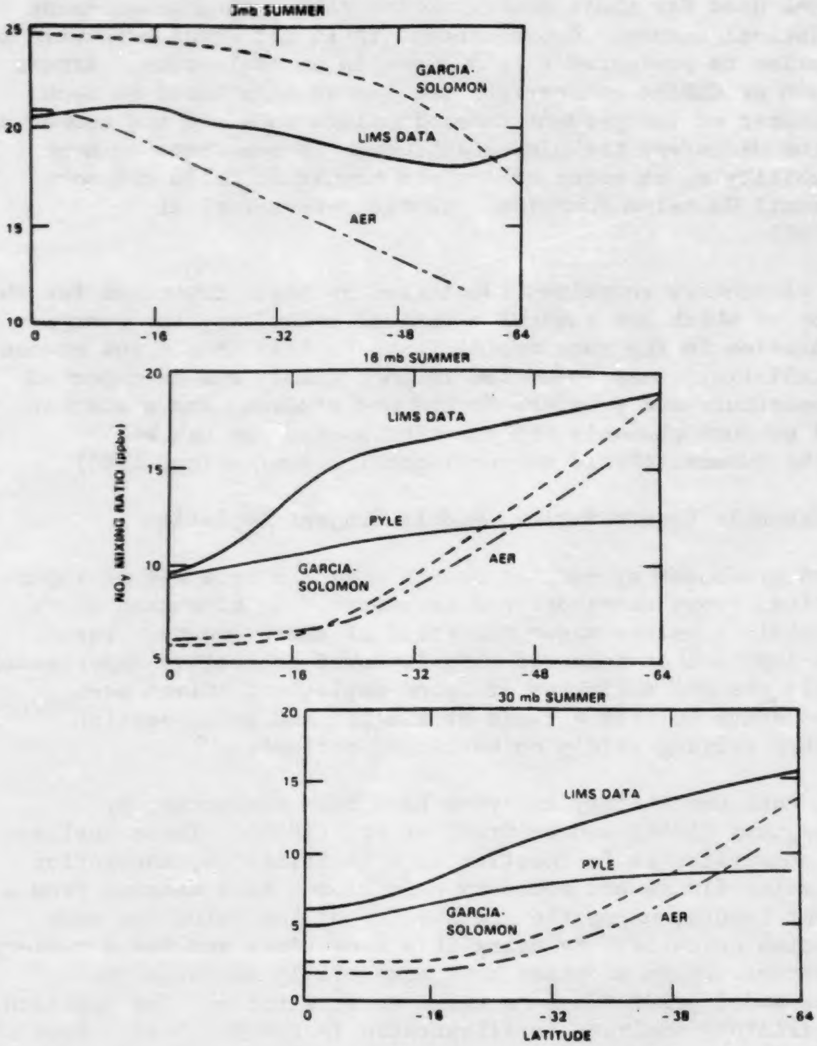
Uncertainties in Chemical and Photochemical Parameters

Clearly, there are **uncertainties in the chemical and photochemical rate parameters and in the mechanisms involved in the atmospheric chemistry. They are one of the major factors in limiting the accuracy of model calculations of species concentrations and ozone perturbations in the atmosphere. Most of the changes in the predicted ozone depletion due to chlorofluoromethanes that have occurred in recent years have resulted from changes in the values of kinetic parameters used in model calculations.** (World Meteorological Organization, 1986)

The uncertainty in the kinetic parameters for the key atmospheric reactions has been reduced greatly over the last 10-15 years due mainly to the rapid development of the techniques used for the direct measurement of radical species in the gas phase and for investigation of their reaction kinetics. Whereas 20 years ago the rates of most radical-molecule reactions were only known to within a factor of 10, today the room temperature rate constants of atmospherically important reactions of this type can be measured within an accuracy of + 10%. Moreover, the number of reactions for which good kinetic data are available have increased tremendously. The consistency in the experimental measurements gives confidence in the data base. There remain problems in reaction rate theory which is not able to explain some of the observed temperature and pressure dependencies. Although there is improved reliability of the data, it should be recognized that the errors in the rate coefficients increase as the temperature diverges from room temperature and that certain reactions, e.g., radical + radical reactions, are intrinsically more difficult to study and consequently are always likely to carry more uncertainty than straightforward radical + molecule reactions. (World Meteorological Organization, 1986)

EXHIBIT 5-46

Latitudinal Gradients in Odd Nitrogen: Models vs Measurements



"There are considerable differences in the distribution of odd nitrogen species that are computed by models of different groups."

Source: NASA (1986).

Difficulties also arise in the study of very slow reactions between radicals and molecules, due to complications such as those arising from heterogeneous effects. (World Meteorological Organization, 1986)

The uncertainty in the rate coefficients for atmospheric reactions results primarily from systematic errors arising from the chemical systems and the techniques used for their determination rather than measurement error of a statistical nature. Consequently, it is not straightforward to assign uncertainties to preferred values given in an evaluation. Errors quotes in the NASA or CODATA evaluations are assessments based on such factors as the number of independent determinations made and the number and reliability of the different techniques employed. Furthermore in most cases, the probability of an error of a given magnitude falls off more slowly than a normal Gaussian function. (World Meteorological Organization, 1986)

For the key elementary reactions identified as being important for the stratosphere many of which are radical + radical reactions, the prospect of reducing uncertainties in the rate coefficients to less than + 10% cannot be considered realistic. Some reduction in uncertainty can be expected from further temperature and pressure dependence studies, and a further understanding of product channels and reaction mechanisms can be anticipated in the future. (World Meteorological Organization, 1986)

For a Range of Testable Uncertainties, Models Project Depletion

The depletion predicted by earlier models uses a single set of input values for kinetics, cross sections, and transport. As discussed above, significant uncertainty exists about the value of these inputs. Past changes in these inputs that occurred with improved laboratory experiments have significantly changed estimates of ozone depletion. Given past history, it makes sense to test a range of kinetic and cross-section inputs, rather than relying solely on best-case estimates.

Fortunately, such uncertainty analyses have been conducted, by Stolarski and Douglass (1986) and by Grant et al. (1986). These analyses recognizing the uncertainties in reaction rate coefficients, absorption cross sections, solar fluxes and boundary conditions, have sampled from a range of different inputs, using the probability of the value for each input as a selection criteria. By doing this many times and for a variety of emission scenarios, these modelers have essentially explored the robustness of the model predictions to these uncertainties. The approach to doing the uncertainty analyses is illustrated in Exhibit 5-47. None of the uncertainty analyses included higher levels of CO2. Different sampling strategies have been used, and different CFC levels analyzed.

Exhibit 5-48 is included in order to give readers a better feel for the nature of this analysis; that is, how uncertainty ranges are derived for rate constants. It shows a **histogram of all of the individual measurements of the room temperature rate coefficient of the reaction O + NO2 - O2 + NO by three different groups (Bemand et al., 1974; Slanger et al., 1973 and Davis et al., 1973). These 62 data points form a distribution that is fit well by either a Gaussian or a log-Gaussian distribution with parameters given by DeMore et al. (1985). These are a central value of 9.4 x 10^{-12}**

EXHIBIT 5-47

Logical Flow Diagram for Monte Carlo Calculations

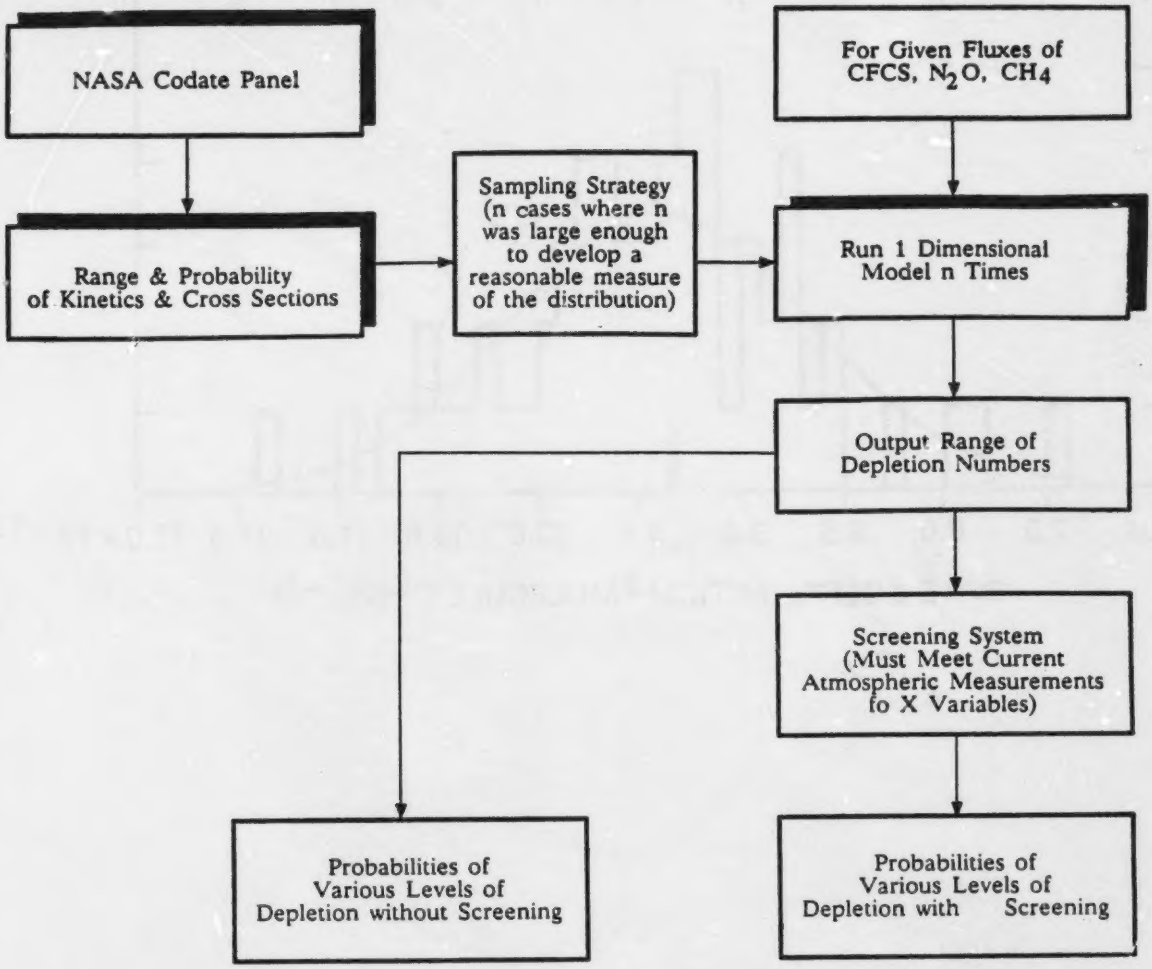
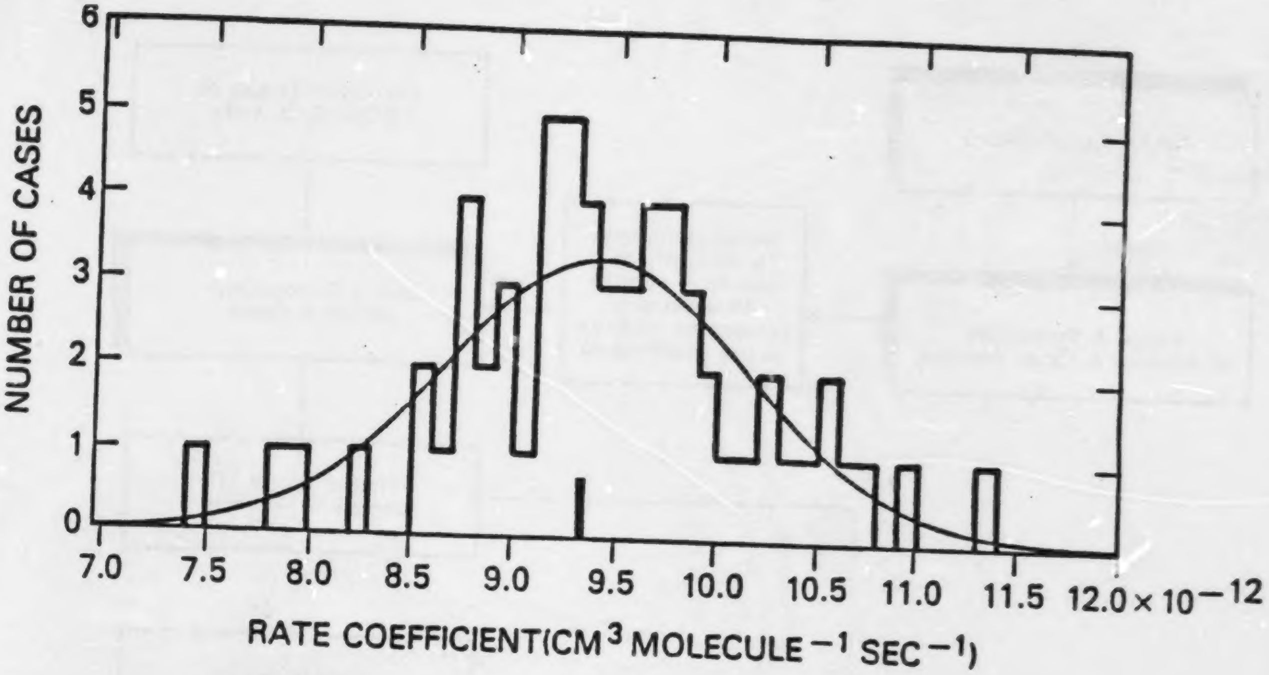

NASA Codate Panel
Range & Probability of Kinetics & Cross Sections
Sampling Strategy (n cases where n was large enough to develop a reasonable measure of the distribution)
For Given Fluxes of CFCS, N_2O, CH_4
Run 1 Dimensional Model n Times
Output Range of Depletion Numbers
Screening System (Must Meet Current Atmospheric Measurements to X Variables)
Probabilities of Various Levels of Depletion without Screening
Probabilities of Various Levels of Depletion with Screening

EXHIBIT 5-48

Histogram of Measurements for a Rate Constant



Histogram of individual data points for the rate coefficient of the reaction O + NO2 ——>P O2 + NO. The measurements have been fit to a smooth curve that forms a probability distribution to be used in Monte Carlo calculations.

Source: Stolarski and Douglass (1986).

and a one- sigma uncertainty of +10%. Also shown in the [exhibit] **is a vertical line representing the mean value which is normally used in a photochemical model. This is not a complete representation of the known information on this reaction.** (Stolarski and Douglass, 1986)

In the uncertainty analysis, rather than using a single value for the rate coefficient described above, different values are used. Some modelers used the Monte-Carlo method, to choose coefficients, others used other sampling methods. **...Of course, a well-measured reaction was chosen for this illustration. Other reactions have only been measured a few times (or only the mean of the actual runs were reported), and the measurements may disagree with one another by substantial amounts. For these cases, it is not obvious how much improvement is obtained by attempting to represent an entire distribution** (Stolarski and Douglass, 1986).

Most of the reactions used in the Stolarski and Douglass model used the chemical kinetic and cross section data and the 1-sigma uncertainties from evaluation 7 of the NASA Panel In Data Evaluation (DeMore et al., 1985). For O2 dissociation, the 1-sigma uncertainty is assumed to be 20% with the Schumann Runge bands and the Herzberg continuum treated independently. The 1-sigma uncertainties in the boundary conditions and assumed dissociation rates are given in [Exhibit 5-49]. (World Meteorological Organization, 1986)

Stolarski and Douglass then applied the Monte-Carlo technique to this model **... to generate a total of 329 cases of varied inputs for calculation of the atmosphere without fluorocarbons, with enough fluorocarbons to give a reasonable steady-state representation of the present atmosphere and with the sequence of increasing fluorocarbon perturbation to investigate the model response to large chlorine amounts.** [Exhibit 5-50] **shows the calculated change in the column content of ozone compared to the no fluorocarbons case as a function of the injected fluorocarbon flux shown in units of the present flux of fluorocarbons 11 and 12 (PFF). The solid curve, labeled the base case, gives the results using the mean values for each input parameter. The dashed curve is the mean ozone depletion obtained from the 329 cases. The mean curve is significantly more linear than the base case curve.** (Stolarski and Douglass, 1986)

Stolarski and Douglass (1986) used current observations to screen their model runs. None of the 329 runs was able to satisfy all the constraints posed by all the observations. Exhibit 5-51 shows the results for the equilibrium values of various levels of CFCs alone. For current emissions, the most common depletion is 3 percent. For 1-sigma deviation (64 percent probability), depletion always occurs. The shaded areas are those cases that passed all the screens except O3 in the upper atmosphere. Note that the screens reduce the variation of results substantially. For a CFC flux of 2 times present values, the screen reduces the range of total column depletion from (+ 1 percent to -60 percent) to (+ 1 percent to -24 percent). Exhibit 5-52 shows the distribution of runs for equilibrium concentrations of 3.5 x current CFC, 1.2 x N2O, and 2 x current CH4. Note that distribution is weighted towards higher values more than lower, and that the worst cases are eliminated if only the cases meeting the screens are used. Exhibit 5-53 represents the change in depletion that would occur for moving from 3.5 x CFC to 3x, from 3x to 2.5x, etc. This exhibit shows that any reduction in emissions of one half of current emissions (that is, from 3x to 2.5x, from 2.5x to 2x, etc.) is likely to lead to less ozone being

EXHIBIT 5-49

Recommended Rate Constants and Uncertainties Used in Monte Carlo Analyses

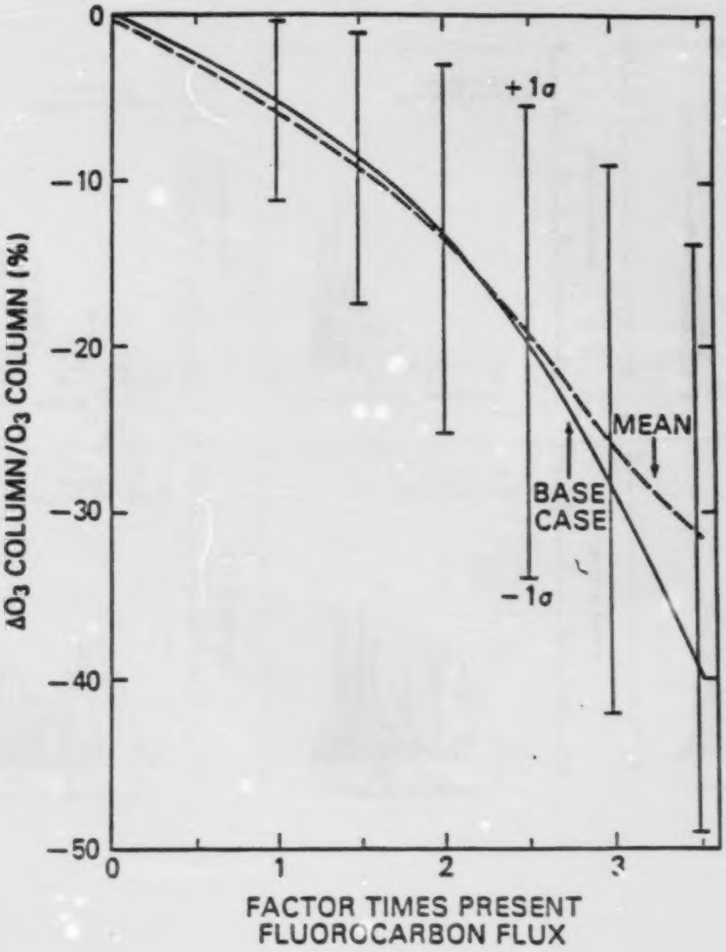
No.	Reaction	Sensitivity Factors			Experimental Uncertainty Factor	Error Contribution Factor
		+1	-1	Av.		
1.	ClO + O = Cl + O2	+0.60	+0.68	+0.64	1.43	+0.23
2.	Cl + CH4 = HCl + CH3	-0.48	-0.46	-0.47	1.16	-0.07
3.	OH + HCl = Cl + H2O	+0.56	+0.79	+0.68	1.32	+0.19
4.	OH + HNO3 = H2O + NO3	-0.51	-0.56	-0.53	1.30	-0.14
5.	OH + HNO4 = H2O + O2 + NO2	-0.16	-0.33	-0.25	2.20	-0.20
6.	O(1D) + M = O(3P) + M	+0.60	+0.63	+0.62	1.32	+0.17
7.	O(1D) + N2O = 2 NO = N2 + O2	-0.51	-2.00	-1.26	1.30	-0.33
8.	ClO + NO2 + M = ClONO2 + M	-0.31	-0.37	-0.34	1.56	-0.15
9.	O2 + hn (S-R) = 2.0	-0.58	-0.85	-0.72	1.40	-0.24

Rate constants recommended in evaluation 7 of the NASA Panel In Data Evaluation. Also shown are the 1 sigma uncertainty bands.

Source: World Meteorological Organization (1986).

EXHIBIT 5-50

Monte Carlo Results:
Change in Ozone Versus Fluorocarbon Flux

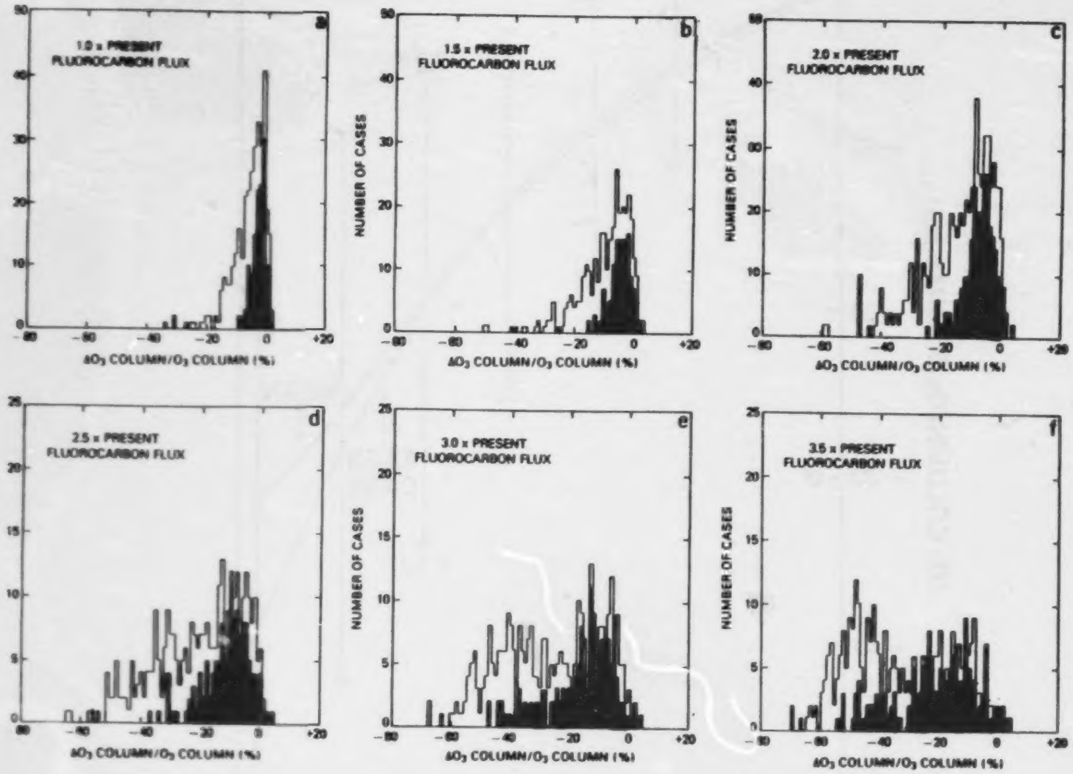


The calculated change in total column ozone as the fluorocarbon flux increases. The sold line shows the base case, which uses the mean value for each input parameter. The dashed line shows the mean depletion from the 329 model runs. The vertical bars show the 1-sigma uncertainty limits.

Source: Stolarski and Douglass (1986).

EXHIBIT 5-51

Monte Carlo Results: Change in Ozone Versus Fluorocarbon Flux

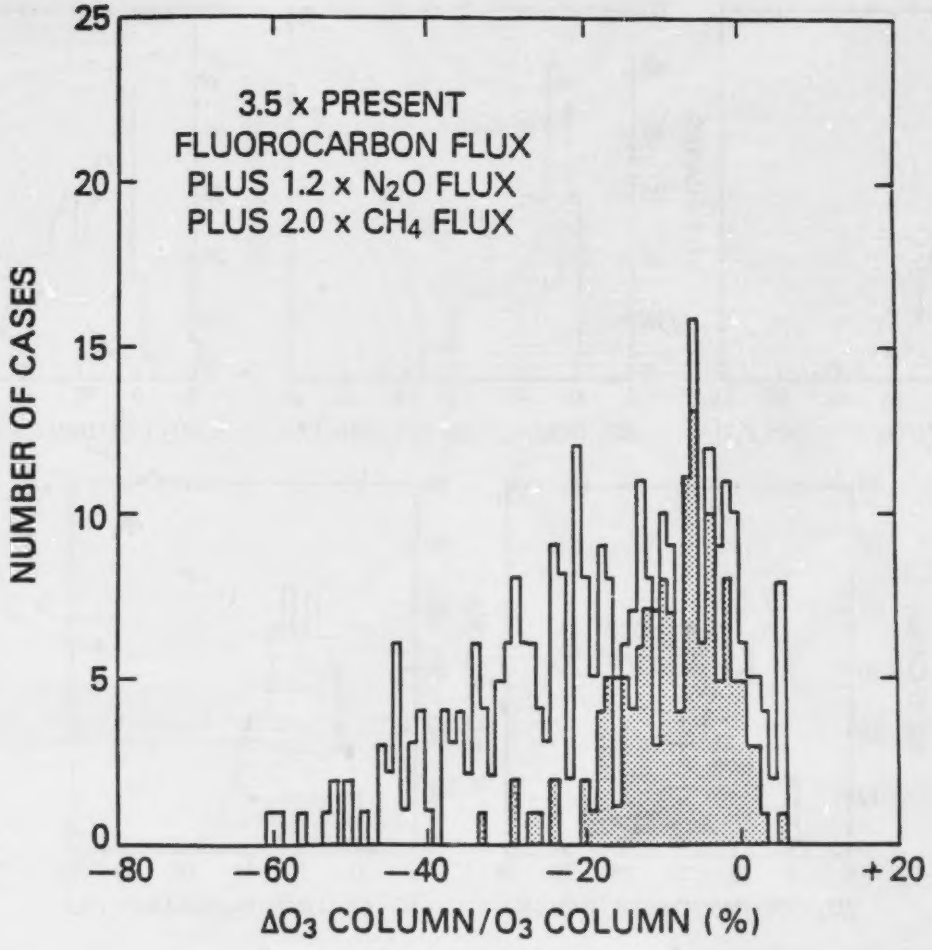


Frequency distributions of Monte Carlo model results for changes in total column ozone as a function of fluorocarbon flux. The shaded areas show the cases for which the NO, NO2, and ClO concentrations all fell within the range of measurements at 25 km.

Source: Stolarski and Douglass (1986).

EXHIBIT 5-52

Monte Carlo Results:
Ozone Depletion for Coupled Perturbations

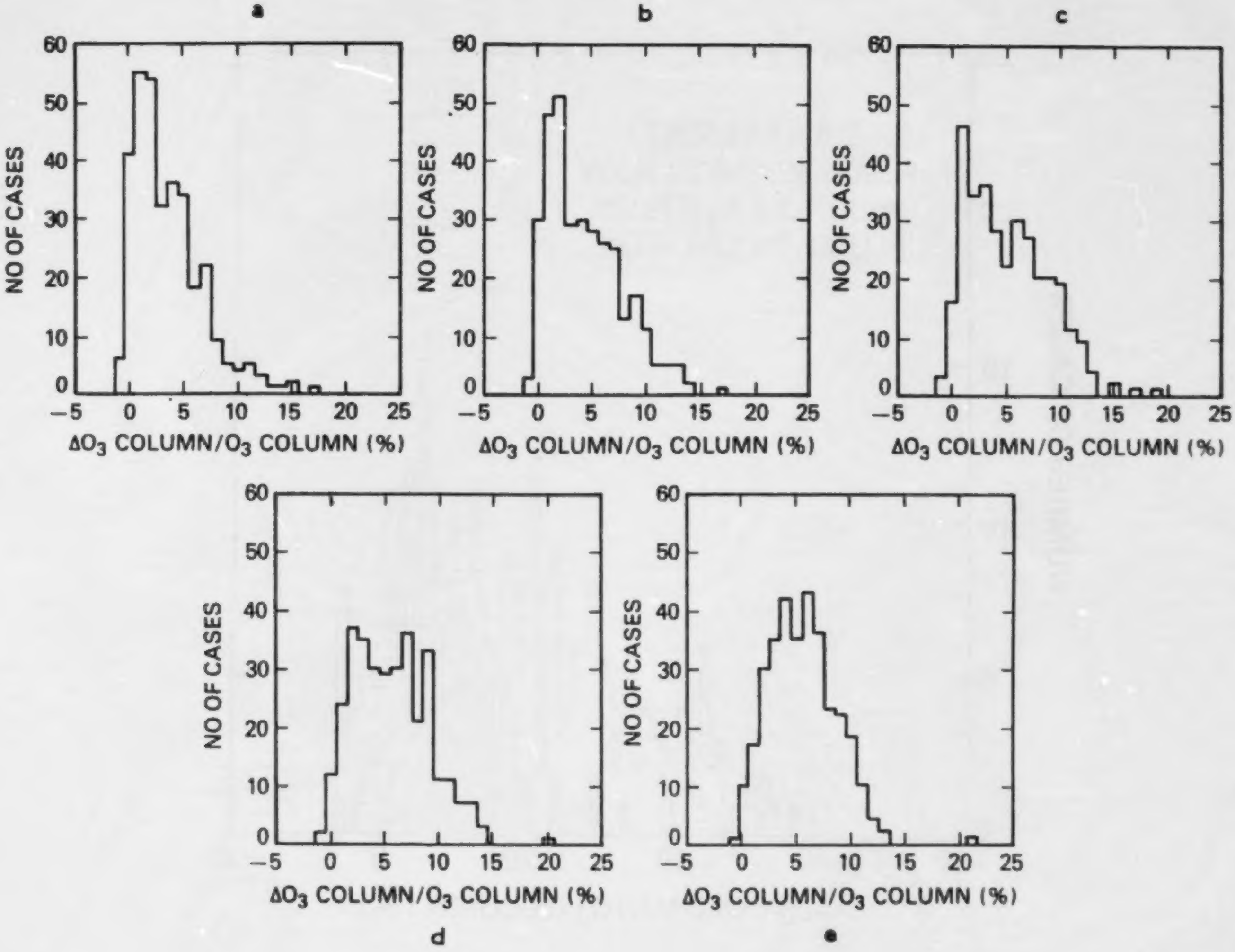


Frequency distribution of Monte Carlo model results for changes in total column ozone for 3.5 times the present fluorocarbon flux, 1.2 x N2O flux, and 2 x CH4 flux. The shaded area shows the cases for which the NO, NO2, and ClO concentrations all fell within the range of measurements at 25 km.

Source: Stolarski and Douglass (1986).

EXHIBIT 5-53

A Monte Carlo Distribution of Column Ozone Changes for Changes in CFC Production



Panel e shows the distribution of change in column ozone for Monte Carlo cases for going from 3.5 x current CFC to 3.0 x current CFC. Panel d shows 3x to 2.5x; c from 2.5x to 2x, b from 2x to 1.5x, a from 1.5x to 1x. For example, in panel e, the majority of cases produce a change in column ozone of 5-10 percent for going from 3.5x CFC to 3x current CFC.

depleted. The distributions of changes in the ozone column look quite similar; for example, going from 3.5 x current to 3.0 x current (panel e) produces very similar distribution as going from 3.0x to 2.5x (panel d). The average amount of depletion prevented by reducing emissions by 0.5 current emissions is about 5 percent. The benefits of a shift in 1/2 current CFC flux are relatively stable across the absolute level of CFCs. Even in the case of going from .5x current emissions to current emissions (panel a), the mean gain in column ozone is close to 4 percent. And the distribution shows that there is little chance that a 0.5 current cut in CFCs will not produce a thickening of the ozone column. In addition, the common shape of the distribution shows that expected change in column ozone is relatively independent of the absolute depletion across the range of input uncertainties Stolarski and Douglass investigated.

Grant et al. (1986) performed two uncertainty analyses. One used 15 ppb Clx, 2 x methane, 1.2 x nitrous oxide and NASA/CODATA kinetics distribution similar to Stolarski and Douglas; the other assumed that all uncertainties in kinetics were reduced to 10 percent, the level the panel has suggested is the practical limit for improving kinetic estimates. Exhibit 5-54 shows the changes in ozone with altitude due to the uncertainty tests (as a percent). Exhibit 5-55 shows the results for unscreened data. When only cases meeting all observational screens are used, uncertainty is reduced to 7.7 ± 6 percent. It is relevant to note that at least eight sets of kinetics and cross sections adequately describe all the apparent observations of the atmosphere.

Exhibit 5-56 shows the cumulative probability of various depletion levels. Approximately 10 out of 100 cases were at around 0.2 percent depletion. For an approximately equal number of cases, depletion was equal to or greater than 20.2 percent. Exhibit 5-57 demonstrates that even if a low level of uncertainty is achieved about kinetics (i.e., ±10 percent), uncertainty will still exist about outcomes.

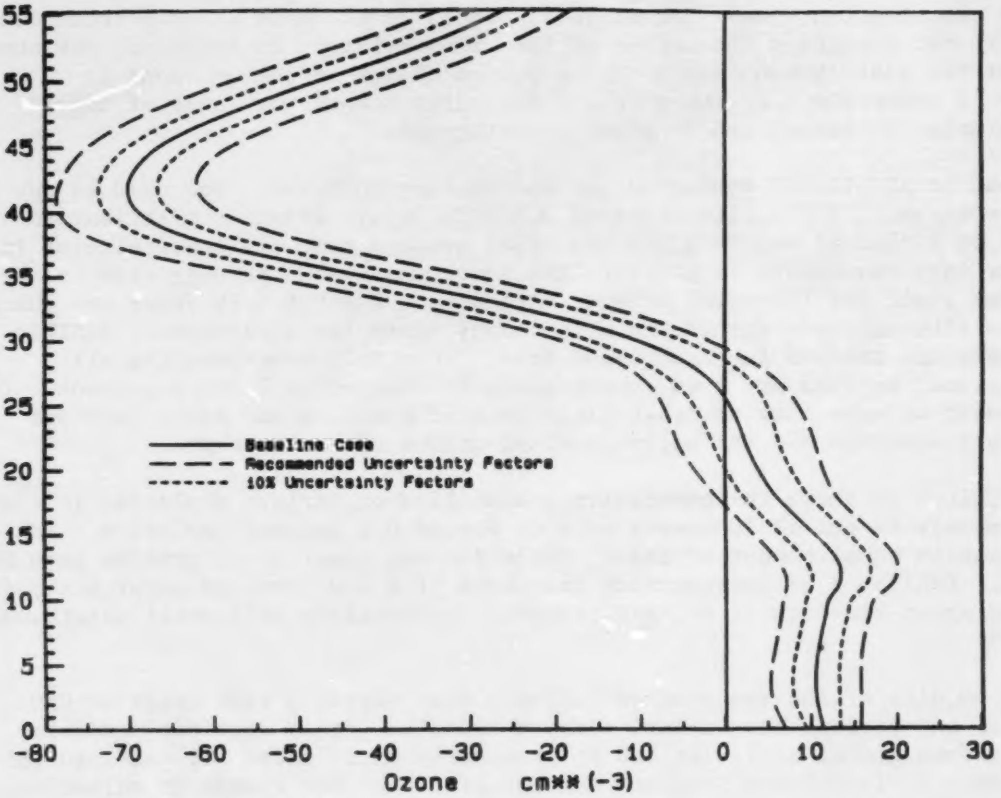
The results of the two studies indicate that across a wide range of CFC scenarios and current uncertainties about kinetics, cross sections and solar flux, average global depletion can be reasonably anticipated for cases in which CFCs grow. Stolarski and Douglass demonstrated that the change in column ozone, for a fixed reduction in CFCs, will vary very little. Thus, even though there is uncertainty about the absolute depletion for any given level of CFCs, there is less uncertainty about how much the column will thicken for reductions in CFCs. This means that the change in column ozone obtained by cutting back emissions is less uncertain than the absolute depletion caused by any level of CFCs.

Uncertainty Analysis of Two-Dimensional Models

To date, the computation costs of performing uncertainty analysis for two-dimensional models have prevented such studies from being undertaken. However, because two-dimensional modelers have used very different transport mechanisms, they have, in effect, created a way to look at the sensitivity of 2-D models to transport uncertainties. Exhibit 5-21 shows the results of the AER and MPIC models; clearly transport makes some difference. The quantity of depletion varies at different latitudes, with the AER model predicting greater depletion further from the poles and the MPIC model predicting greater depletion towards the equator. Both, however, have a gradient of increasing depletion as one

EXHIBIT 5-54

Monte Carlo Results:
Changes in Ozone by Altitude

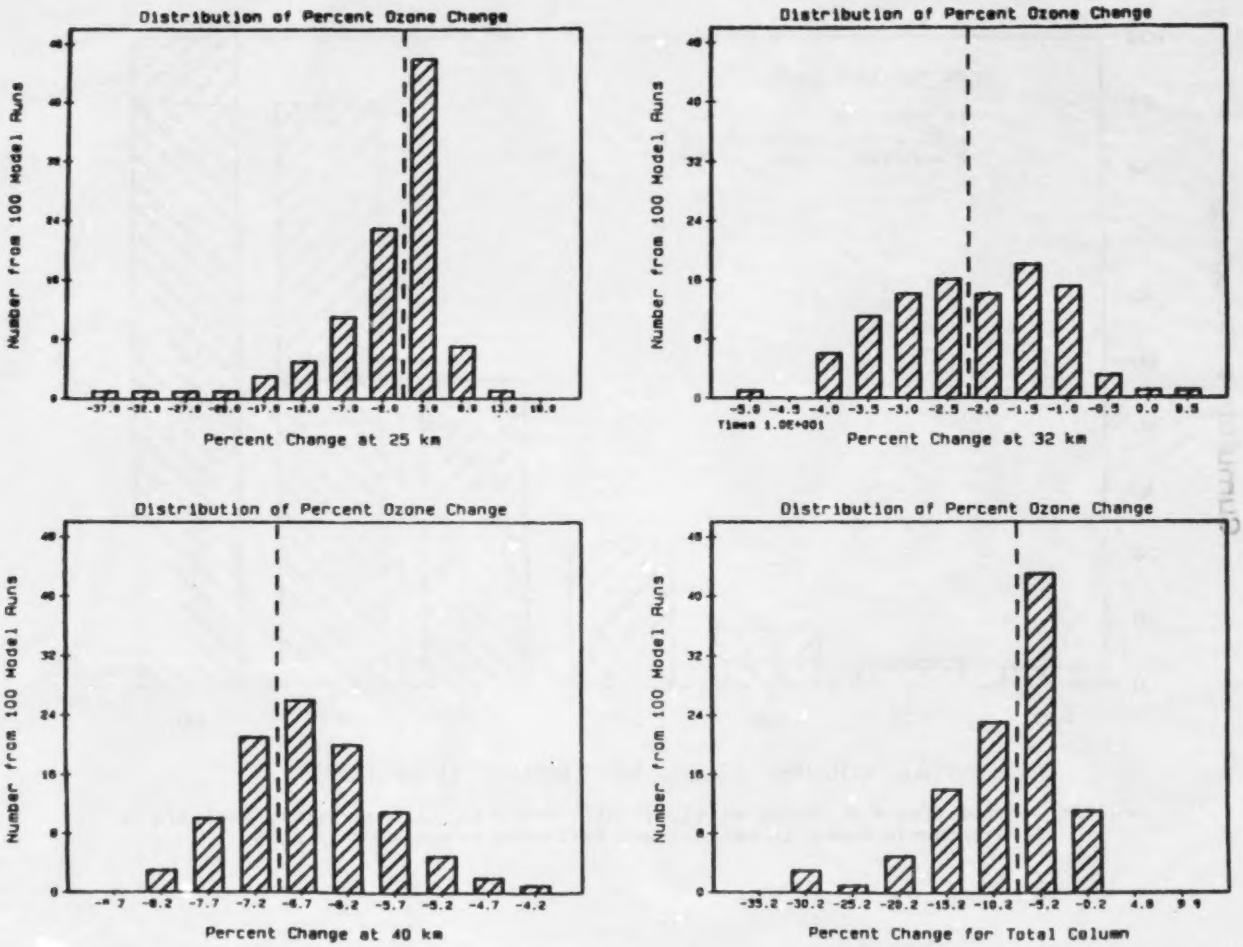


Results from Monte Carlo analysis of uncertainties regarding rate constants. Solid line shows calculated changes in ozone by altitude for mean values of input parameters. Dashed lines show calculated changes for recommended uncertainty factors. Dotted lines show calculated changes for uncertainties which have been reduced to 10 percent. Perturbations are: 15 ppbv Clx, 2x CH4, and 1.2x N2O.

Source: Grant, Connell, and Wuebbles (1986).

EXHIBIT 5-55

Monte Carlo Results: Changes in Ozone by Column and Altitude, Unscreened Data

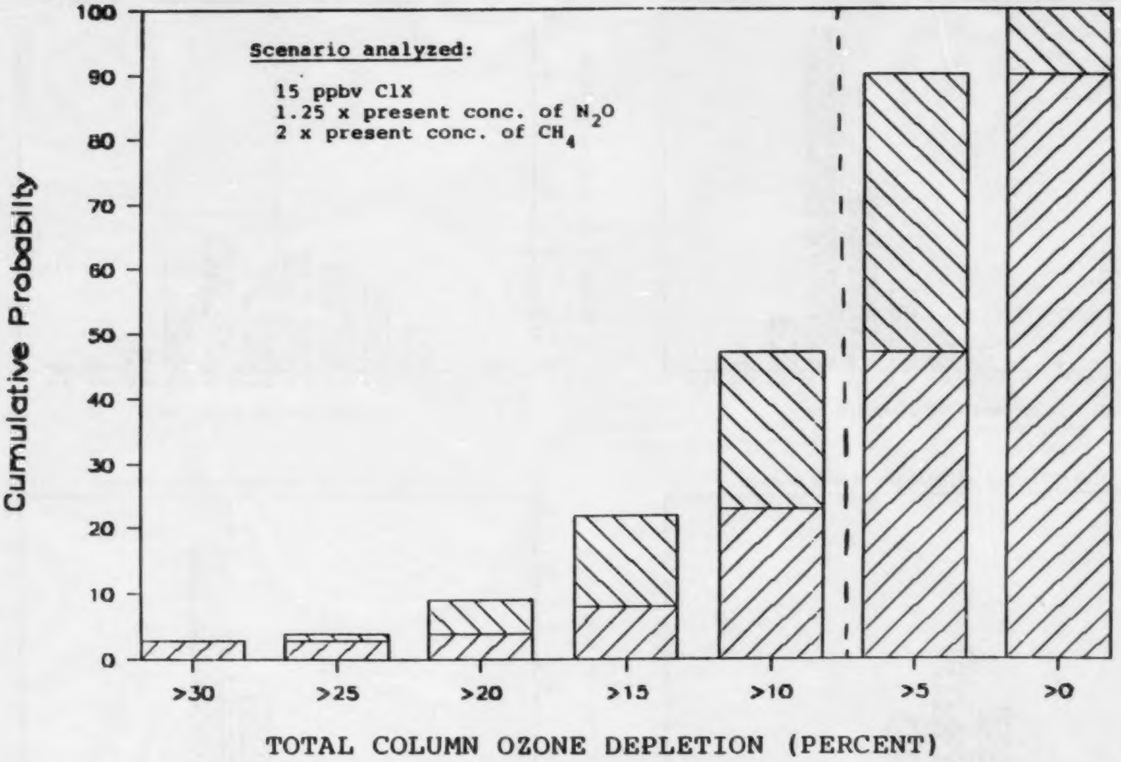


Frequency distributions of Monte Carlo model results for changes in ozone. Top left panel shows results for 25 km, top right for 32 km, bottom left for 40 km, and bottom right for total column ozone. Perturbations are: 15 ppbv Clx, 2x CH4, and 1.2x N2O.

Source: Grant, Connell, and Wuebbles (1986).

EXHIBIT 5-56

Monte Carlo Analysis With the LLNL 1-D Model



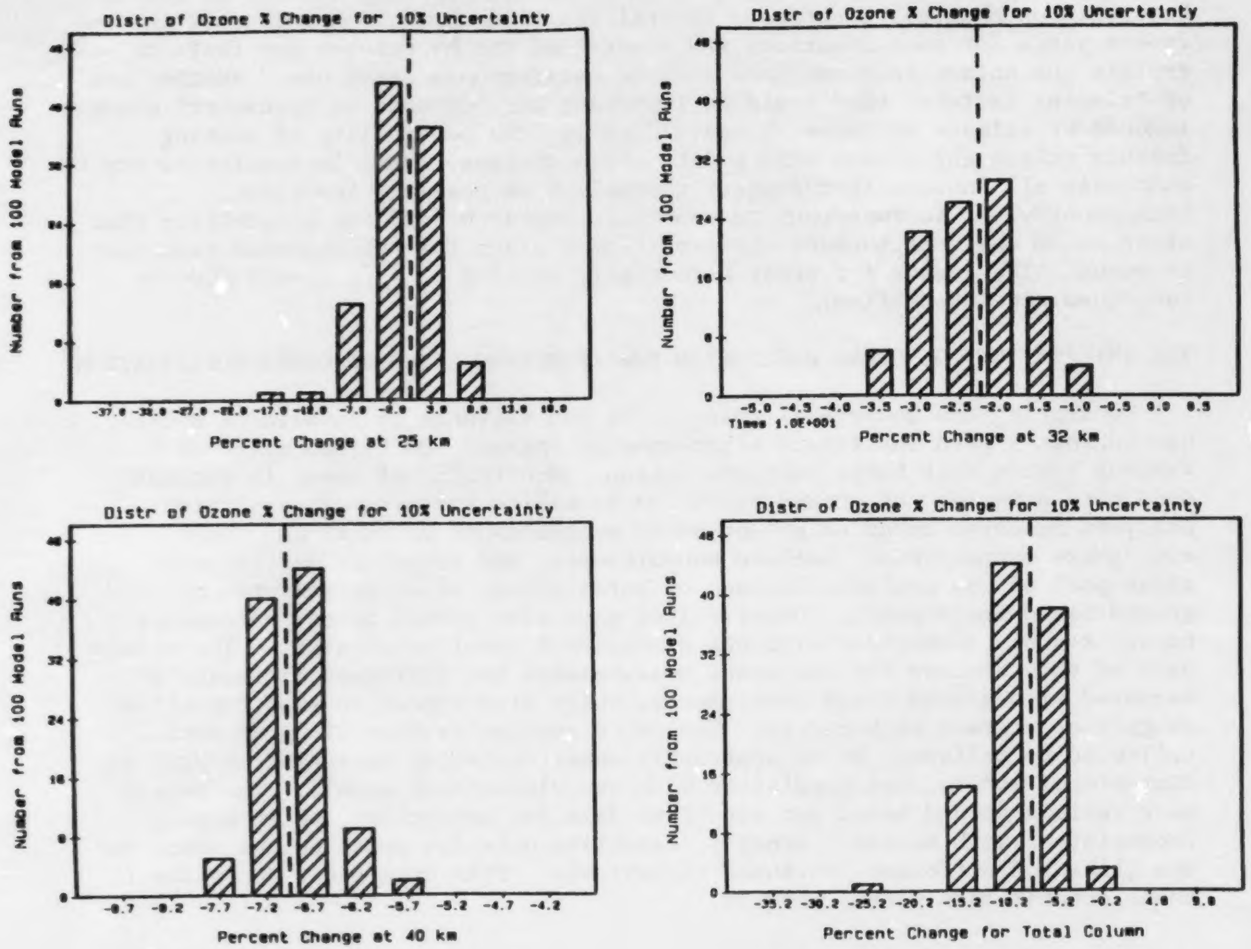
SOURCE: Adopted from K.E. Grant et al. (1986) "Monte Carlo Uncertainty Analysis of Stratospheric Ozone in Ambient and Perturbed Atmospheres", LLNL.

The cumulative probability of ozone depletion cases unscreened for meeting current atmospheric measurements is shown above. For example, the chance of a depletion greater than 10 percent occurring is about 50 percent. The dashed line indicates the value of depletion predicted for current kinetics and other inputs.

Source: Adapted from Grant, Connell, and Wuebbles (1986).

EXHIBIT 5-57

Monte Carlo Results: Changes in Ozone by Altitude



Frequency distributions of Monte Carlo model results for changes in ozone, when uncertainties in input parameters are reduced to 10 percent. Top left panel shows results for 25 km, top right for 32 km, bottom left for 40 km, and bottom right for total column ozone. Perturbations are: 15 ppbv Clx, 2x CH4, and 1.2x N2O.

Source: Grant, Connell, and Wuebbles (1986).

moves away from the equator. Thus, while the uncertainty in transport clearly produces different gradients, at least for these models, the results robustly predict depletion.

Missing Factors

The possibility of missing factors in the models used to project future ozone levels is a difficult one. The most likely "missing factor" is some heterogenous chemical reaction. Several reactions have been suggested in recent years for such reactions and several of the hypotheses put forth to explain the Antarctic ozone hole include heterogenous reactions. Another set of "missing factors" that could be important are "dynamic or transport" changes induced by climate or ozone change. Clearly, the possibility of missing factors exists and always will exist. Nevertheless, it is imperative to try to encompass all factors that suggest themselves as possibly important. Consequently, it is important to undertake research into the possibility that aerosols in the stratosphere are providing a place for heterogenous reactions to occur. The search for other potentially missing factors should also be continued and intensified.

THE IMPLICATIONS OF OZONE MONITORING FOR ASSESSING RISKS OF OZONE MODIFICATION[2]

Monitoring can do several things: it can validate or invalidate models; it can suggest a path for future stratospheric change; and it can serve as a warning system that helps initiate action. Monitoring of ozone is currently done with a variety of ground-based and satellite systems. This section analyzes research based on ground-based measurements of total and upper atmosphere ozone trends, balloon measurements, and satellite measurements. The first part of the analysis focuses on total column ozone as measured by ground-based instruments. Observations made with ground-based instruments appear roughly consistent with one-dimensional model predictions. The second part of this section reviews ozone measurements for different altitudes as measured with ground-based instruments, which also appear to show depletion roughly consistent with models. The third section reviews altitude data collected by balloons, which apparently shows depletion inconsistent with one dimensional models, but consistent with two-dimensional models. The fourth part reviews ground-based and satellite data for Antarctica, which appear inconsistent with models. Finally, satellite data for total column ozone for the globe and different latitudes is reviewed. This data shows decreases in ozone greater than models predict.

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[2] The scientific description in this section of the risk assessment is severely out of date. Major reassessments on Antarctic ozone and global trends are underway in the scientific community. EPA plans to issue a risk assessment on these areas in 1988. Readers may wish to skip this section since it is not reflective of current thinking. It is left in this document for the purpose of demonstrating what assessment was made of this data in the 1986-1987 timeframes. Discussion of the policy implications of monitoring data and Antarctica remains the same; however, EPA has assumed that current models are accurate for decisionmaking and that it is premature to argue that Antarctica or global trends invalidate current models.

Analyses of Global Total Ozone with Ground Based Instruments

Analyses of total column ozone using Dobson instruments must convert the irradiances received by the spectrometer into a total column ozone reading. Reading from each station must be combined to represent seasonal and yearly averages for that location. To develop global averages, station values must be locally weighted and averaged. At each one of these stages, assumptions and choices must be made which can influence the outcome of the analysis.

Ground Based Global Ozone Depletion Estimates Appear Consistent with One Dimensional Model Predictions

Over the past several years there have been several studies conducted in an attempt to detect any evidence of a total ozone trend (e.g. Hill et al., 1977; Reinsel, et al., 1981; St. John et al., 1982, Angell and Korshover, 1983; Bloomfield et al., 1983). Most recent statistical analyses have adopted a time domain approach to estimating a global trend. The ozone value Xt,j at time t and observing station j is represented by Xt,j - lj ht + et,j where ht represents a predicted global trend ... at station j; and et,j represents an error process to account for other influences on ozone. The et,j series is typically assumed to be an autoregressive process (e.g., Hill et al., 1977; Reinsel et al., 1981; St. John et al., 1982). This model is fit separately to the ozone record from each station, and a global trend estimate is obtained by combining the station values ej. Bloomfield et al., (1983), on the other hand, introduce a frequency domain statistical model. This model extends variance-components analysis to the time series case and incorporates both temporal and spatial association found in the ozone data. A key feature of this model is the inclusion of a common global term representing natural global variations in ozone. (World Meteorological Organization, 1986).

Reinsel et al., (1981) found an increase of 0.28% in global total ozone over the period 1970-1978 with a standard error of 0.67%, while St. John et al., (1982) found an increase of 1.5% with a standard error of 0.5% from '70-'79 and Bloomfield et al., (1983) found an increase of 0.1% for the same period with a standard error of 0.55%. Thus there is little overall support for the suggestion of a statistically significant trend in total ozone. (World Meteorological Organization, 1986).

Reinsel et al., (1985 - personal communication) have recently extended the analysis using data through 1983. Time series models were used to obtain a trend estimate for each station, where level shifts to account for instrument recalibration were also included in the model for five stations (Mt. Louis, Mt. Abu, Lisbon, Buenos Aires, and Hradec Kralove). The overall trend estimate for total ozone change over the entire period 1970-1983, with associated 95% confidence limits, is (-0.003 + -1.12) % per decade. (World Meteorological Organization, 1986).

Trend analyses were also performed using the f10.7 solar flux series and the sunspot number series separately as explanatory variables for the total ozone series at each station. Results were quite similar in both cases, and the overall total ozone trend estimates for the period 1970-1983 are summarized as follows, (World Meteorological Organization, 1986):

(-0.00 ± 1.12) % per decade with no solar effect in model
(-0.17 ± 1.10) % per decade with f10.7 solar flux in model
(-0.14 ± 1.08) % per decade with sunspot series in model

The f10.7 solar flux series (as well as the sunspot series) was found to be mildly related to total ozone overall, with the estimated effect of f10.7 solar flux on total ozone (averaged over 36 stations) equal to (0.63 + 0.53)% ozone change per 100 units of F10.7 solar flux. This estimate corresponds to about a one percent change in total ozone from solar cycle minimum to maximum. (World Meteorological Organization, 1986).

These analyses all indicate no significant overall trend in total ozone during the fourteen year period 1970-1983, and suggest a mild relation between total ozone and f10.7 solar flux. The trend estimates are about 0.2% per decade more negative with the inclusion of data for 1983 than comparable estimates based on data through 1982. (World Meteorological Organization, 1986).

A major question of the statistical analyses has been the general lack of global coverage of the ground-based observations suggesting possible spatial biases. For the most recent trend estimates given above by Reinsel et al., (1985, personal communication). [Exhibit 5-58] shows a plot of the trend estimates as a function of latitude. Altogether, there does not seem to be any latitudinal effect, but if we examine this diagram by region we see an interesting pattern. For example, all of the North American stations are below the Indian network as are 6 of 7 European stations. While the analysis of Reinsel et al., (1981) takes this type of regional networking into consideration, it suggests that more consideration should be given to the representativeness of the data set. (World Meteorological Organization, 1986). In addition, it is clear that there is very poor coverage in northern latitudes, with no stations in the sample significantly above 60°N. Coverage in the southern hemisphere is worse.

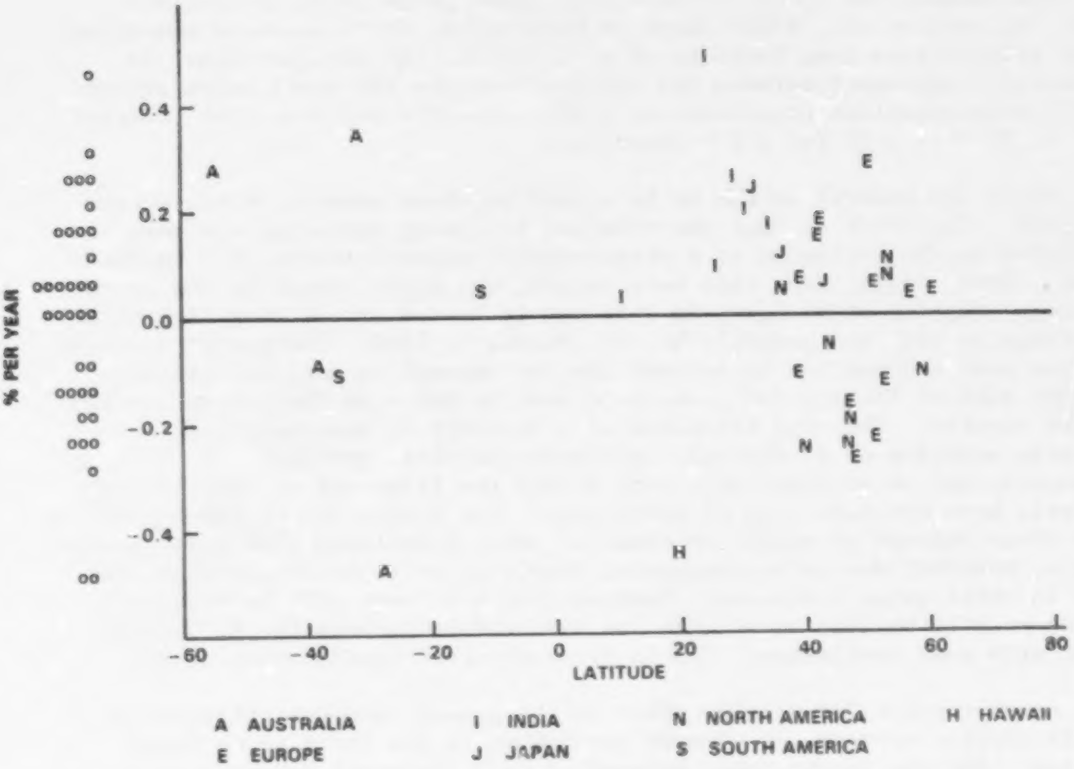
Analysis of Ozone Trends at Different Altitudes with Ground Based Instruments

Although there have been several recent analyses of Umkehr data (eg Angel and Korshover, 1983b; Reinsel et al., 1983; Bloomfield et al., 1982), these have been limited in that they did not consider the impact of stratospheric aerosols on the observations. This has been discussed by Deluisi (1979) and Dave et al., (1979) and it has been concluded that aerosols tend to induce significant negative errors in the Umkehr measurements in the uppermost layers 7-9, with the largest percentage error occurring in layer 9. (World Meteorological Organization, 1986).

Based on this, Reinsel et al., (1984) have completed a statistical analysis of the Umkehr data where atmospheric aerosols are taken into account. In the statistical trend analysis, time series models have been estimated using monthly averages of Umkehr data over the past 15 to 20 years through 1980 at each of 13 Umkehr stations and at each of the five highest Umkehr layers, 5-9, which cover an altitude range of approximately 24-48 km. The time series regression models incorporate seasonal, trend, and noise factors and an additional factor to explicitly account for the effects of atmospheric aerosols on the Umkehr measurements. At each Umkehr station, the explanatory series used in the statistical model to account for the aerosol effect is a 5 month

EXHIBIT 5-58

Ozone Trend Estimates by Latitude



Recent ozone trend estimates from ground-based observation networks. Horizontal axis shows latitude of measurement. Legend identifies each site. Vertical axis shows histogram of trend estimates.

Source: World Meteorological Organization, (1986).

running average of the monthly atmospheric transmission data at Mauna Loa, Hawaii, the only long running aerosol data available. A random effects model is used to combine the 13 individual station trends for each Umkehr layer. The analysis indicates statistically significant trends in the upper Umkehr layers 7 and 8 of the order of -0.2 to -0.3% per year over the period 1970-1980, with little trend in the lower layers 5 and 6. (World Meteorological Organization, 1986).

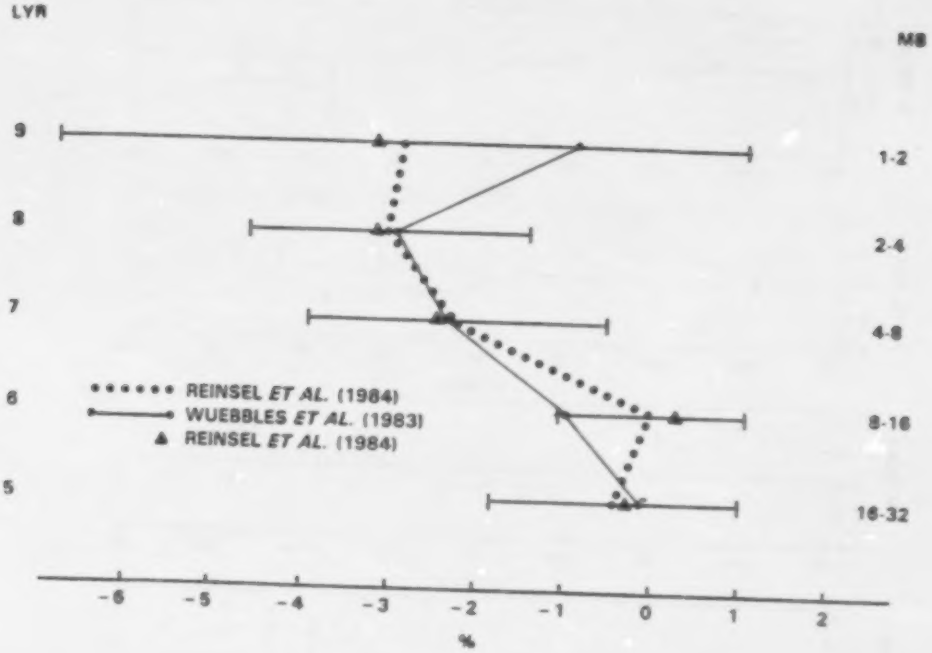
The results are [repeated here and] shown graphically in [Exhibit 5-59] (Reinsel et al., 1983) where we have added, for comparison numerical model calculations from Wuebbles et al., (1983). We see that there is substantive agreement between the observations and the model calculations. (World Meteorological Organization, 1986). Readers may also wish to refer back to Exhibit 5-35 for a 2-D comparison.

There are several points to be raised on these results of the Umkehr analysis. The first is that the results, including the sign, are very sensitive to the inclusion of a stratospheric aerosol impact (i.e. Reinsel et al., 1983, 1984). For this data record, the major impact is due to the volcanic eruption at Mt Agung in 1963 and to lesser extent that of Tierra Del Fuego in 1974 and possibly Mt. St. Helens in 1980. The use of a single station such a Mauna Loa to account for the aerosol on a global basis is fraught with difficulty and great care must be taken on the interpretation of the results. This was evidenced most recently by the events of the volcanic eruption of El Chichon. Attempts (DeLuisi, personal communication) to consider this even within the framework of the previous analysis have not been free of difficulty. One suggestion by DeLuisi is that there existed an actual decrease of ozone associated with the volcanic debris, possibly due to heterogeneous chemistry or injected chlorine, but this is still quite uncertain. Considerably more work will be required before we will be able to utilize the Umkehr data through the El Chichon event with some confidence. (World Meteorological Organization, 1986).

Another point for consideration is the global representativeness of the 13 station network, an element touched on in the total ozone trend section. For the Umkehr data, Reinsel et al., (personal communication) have examined the spatial sampling by examining the approximate 4 year period of the global SBUV data. Their results are presented in [Exhibit 5-60] where the trends over the period November '78 - April '82 have been determined from SBUV zonal averages. Superposed on these curves are the values determined in 10° x 10° longitude/latitude boxes from the SBUV data that includes the Umkehr site. In layer 8, for example, we see that the North American and European stations are biased on the high side of the curve and that Japanese stations tend to bring the overall average into line. Thus, the overall results can be very sensitive to the availability of the stations. This is taken to extreme in the Southern Hemisphere where we see that the Australian station happens to coincide with the relative peak in the zonal average. Because of this fortuitous sampling the overall station average is rather close to the total SBUV area weighted trend. That the ground-based results are so sensitive to the spatial sample is, of course, precisely why the NOAA operational satellite ozone measurement program was initiated. This will be discussed further below. (World Meteorological Organization, 1986).

EXHIBIT 5-59

Changes in Ozone from 1970 to 1980: Umkehr Measurements and Model Calculations

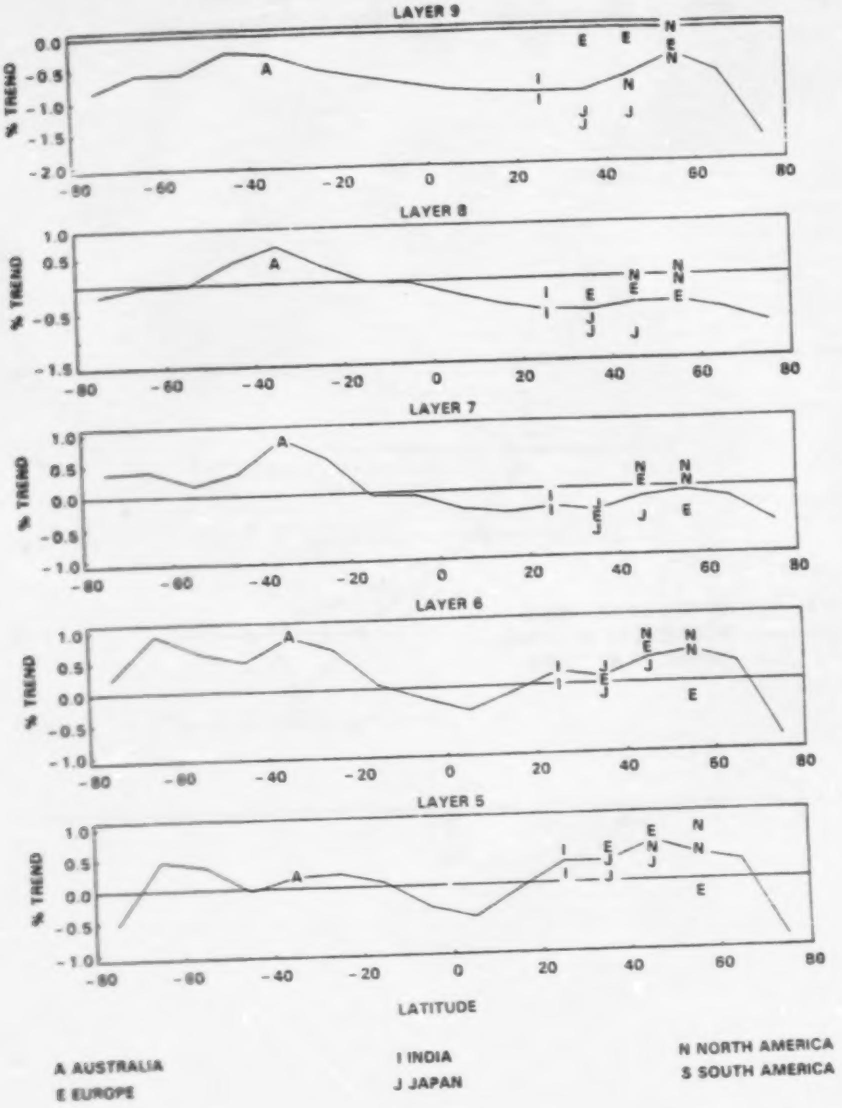


Changes in ozone by altitude for 1970 to 1980. The data "analysis indicate statistically significant trends in the upper Umkehr layers 7 and 8 of the order of -0.2 to -0.3 percent per year over the period 1970-1980, with little trend in the lower layers 5 and 6.

Source: World Meteorological Organization, (1986).

EXHIBIT 5-60

SBUV Zonal Trends Estimates Versus "Umkehr Station Blocks"



Ozone trend estimates for November 1978 to April 1982, as determined by SBUV data, are indicated by solid line. Superimposed letters indicate results from Umkehr stations.

Source: World Meteorological Organization, (1986).

As the final element in this section we discuss the inclusion of a solar flux variation within the trend analysis. For the Umkehr data, Reinsel et al., (personal communication) have included the f10.7 cm solar radio flux as an additional independent variable. (World Meteorological Organization, 1986).

For each Umkehr layer, 5 to 9, and for a given Umkehr station, the model was used:

$$Y_t = m + S_t + ex_t + n1V_{1t} + n2V_{2t} + N_t$$

Where

Y_t = monthly average for month t of a station's observations at a given layer

S_t = seasonal component (annual and semi-annual)

xt = 0 to $t < T$ (T denotes 12/1696)
= $(t - T)/12$ for $t > T$

e = annual rate of change parameter (trend)

V_{1t} = a smoothed version of the transmission data at Mauna Loa

n1 = a parameter providing an empirical measure of the aerosol effect on Umkehr data

V_{2t} = monthly mean of 10.7 cm solar radio flux (2800 MHz)

n2 = a parameter for an empirical measure of the solar effect on Umkehr data

N_t = an autocorrelated noise term, modelled as an autoregressive process to account for non-independence of data

m = intercept which is very close to the average value

A term to account for a shift in mean level due to instrument recalibration was also included in the model for some stations, as described above. (World Meteorological Organization, 1986).

The trend estimates including the solar flux series are shown in [Exhibit 5-61] as the solid triangles (Reinsel et al., personal communication). We see that there is very little impact on the decadal trend with this term added. The overall estimates for the regression coefficients of the solar flux series with accompanying 95 percent confidence intervals are 0.81 + 2.56, 0.46 + 1.80, 2.04 + 1.32, 1.53 + 0.78 and 1.18 + 0.86 percent, respectively, for layers 9 through 5. These coefficient estimates represent percentage change in ozone per 100 units change in solar flux. The solar effect is largest in layer 7, and statistically significant in both layers 7 and 6. The estimates correspond to a solar effect on ozone from solar cycle minimum to maximum of about 1.3, 0.8, 3.4, 2.5, and 2.0 percent respectively, for layers 9 through 5. (World Meteorological Organization, 1986).

EXHIBIT 5-61

Ozone Trend Estimates and 95% Confidence Intervals

Layer	KM	95% Interval (%/yr.) (Without Intervention)	95% Interval (%/yr.) (With Intervention)
Above 6B	35+	-0.05 ± 0.38	0.22 ± 0.56
6B	30-35	0.04 ± 0.33	0.27 ± 0.54
6A		0.22 ± 0.31	0.46 ± 0.51
5B	25-30	0.15 ± 0.17	0.18 ± 0.21
5A		0.05 ± 0.18	-0.02 ± 0.27
4B	20-25	-0.07 ± 0.15	-0.16 ± 0.22
4A		-0.21 ± 0.22	-0.30 ± 0.21
3B	15-20	-0.33 ± 0.25	-0.48 ± 0.26
3A		-0.56 ± 0.31	-0.71 ± 0.27
2B	10-15	-0.30 ± 0.53	-0.48 ± 0.49
2A		-0.17 ± 0.67	-0.64 ± 0.75
1D	5-10	0.93 ± 1.04	0.08 ± 0.88
1C		1.44 ± 1.23	0.57 ± 0.74
1B	0-5	1.43 ± 0.87	0.66 ± 0.53
1A		1.72 ± 1.17	0.75 ± 0.83

Combined ozone trend estimates in the various layers along with their 95% confidence limits. We see that with and without the data intervention at the 4 Canadian sites the negative trends in the lower stratosphere appear statistically significant and of the same magnitude, about -5% per decade. In the lower troposphere, however, the values are very different although they remain positive.

Source: World Meteorological Organization (1986).

It is not at all clear as to why the solar flux term should have a significant regression coefficient in layers 7 and 6 and not in layers 9 and 8, and rises serious questions on the effect of the solar flux variations. (World Meteorological Organization, 1986).

Balloon Data for Ozone Trends at Different Altitudes

In a recent update of ozone variations determined from balloonsondes, Angell and Korshover (183) determined that in the tropospheric layer of north temperate latitudes, 2-8 km, the data suggest a 12% increase in ozone between 1970 and 1981. This is accompanied by a 1-3% decrease in the region 16-32 km. Since then, several on-going studies have focused on the quality of the ozonesonde data for trend detection (Tiao et al., personal communication; Logan, 1985) and the discussion is presented here with the author's kind permission. Formal publication is planned for the near future. From Tiao et al., Ozonesonde data from 13 stations have been processed to obtain monthly averages of ozone in 14 fractional Umkehr layers, (1A, 1B, 1C, 1D, 2A, 2B, 3A, 3B, 4A, 4B, 5A, 5B, 6A, 6B), (e.g. [Exhibit 5-61] and an additional layer above 6B. For each station, the daily sonde data (in partial pressure) were first integrated into ozone readings (in Dobson units) within each layer, and monthly averages for each layer were then computed from the integrated readings. The data were screened to meet the following criteria: (World Meteorological Organization, 1986).

-- The correction factor was between .8 to 1.3 for ECC and .8 to 1.4 for Brewer.

-- The balloon reached a burse level of 15.8 mbar (top of layer 5B).

-- There were no zero partial pressure readings recorded in each daily sondes.

-- The total ozone reading for the daily sonde data had a nonzero value.

The station locations, data span and methods of measurement are given in [Exhibit 5-62] (Tiao et al., personal communication), where the Canadian stations changed from the Brewer system to the ECC at the designated times. (World Meteorological Organization, 1986).

One of the first elements examined were the correction factors for the various instruments and, as examples of this parameter, we present in [Exhibit 5-63] (Reinsel et al., personal communication), the results at Goose Bay, and Hohenpeissenberg. At Goose Bay we see that the individual months show large variations with a small tendency for decrease till 1980 where the change to ECC was effected. The impact of this change will be discussed further below. For Hohenpeissenberg the diagram also shows some interesting month-to-month variations and we note, in particular, the tendency for the corrections to increase during the first few years followed by the strong minimum in the late '70's. (World Meteorological Organization, 1986).

The cause of these tendencies in the correction factors is unclear and may be related to instrument manufacture, personnel changes or changes in the Dobson

EXHIBIT 5-62

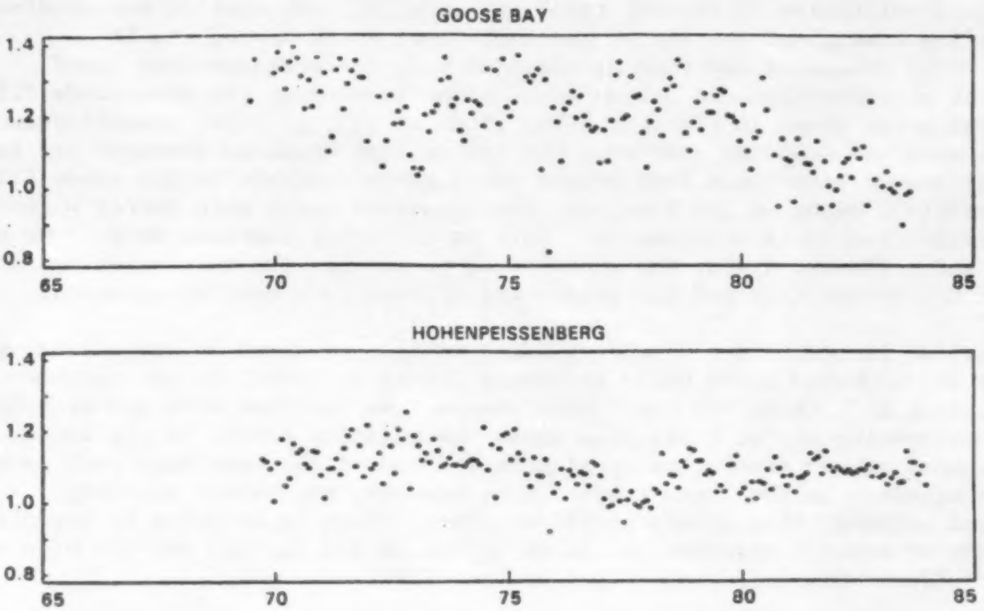
Ozone Balloonsonde Stations

Station	Data Span	Methods
Hohenpeissenberg	1/70-2/83	Brewer
Biscarrosse	3/76-1/83	Brewer
Lindenberg	1/75-2/83	Brewer
Payerne	9/68-12/81	Brewer
Aspendale	6/65-5/81	Brewer
Churchill	10/73-1/83	Brewer/ECC 9/79
Edmonton	10/70-12/82	Brewer/ECC 9/79
Goose Bay	6/69-12/82	Brewer/ECC 12/80
Resolute	1/66-1/83	Brewer/ECC 12/79
Wallops Island	5/70-4/82	ECC
Kagoshima	1/70-12/82	ECC
Sapporo	12/68-12/82	ECC
Tateno	3/68-12/82	ECC

Source: World Meteorological Organization (1986).

EXHIBIT 5-63

Correction Factors for Balloonsonde Measurements



Shown for Goose Bay and Hohenpeissenberg.

Source: World Meteorological Organization, (1986).

system. The major point is that we can not expect the correction factors to be random about some average value and that we will have to consider, in detail, the possible impacts of these variations. As Hilsenrath et al., (1984) have indicated, this brings into question whether or not the factors should be applied as they are, as a percentage change to the profile, or in some height dependent manner. (World Meteorological Organization, 1986).

The above notwithstanding, trend estimates (1970) have been obtained from the monthly averages using standard models reported previously with and without an intervention at the 4 Canadian sites for the changes of measurement method. As a cross-validation an overall trend estimate for each station was obtained by calculating a weighted average of the individual estimates of the 15 layers.These estimates may then be compared with the corresponding trend estimates obtained from the Dobson total ozone reading on the ozonesonde file. The results are shown in [Exhibit 5-64] (Tias et al., personal communication). For the nine non-Canadian stations, the trends from weighted averages are in close agreement with those from Dobson total ozone readings on the sonde file. For Churchill, Edmonton and Resolute, the agreement seems much better without the intervention level adjustments. This is in direct contrast to what we would expect and reflects, again, the question as to whether the correction factors between the Brewer Mast and ECC sondes are applied in a consistent manner.

Finally, in [Exhibit 5-61 above] (Tias et al., personal communication) we present the combined ozone trend estimates ([Exhibit 5-64]) in the various layers along with their 95% confidence limits. We see that with and without the data intervention at the 4 Canadian sites the negative trends in the lower stratosphere appear statistically significant and of the same magnitude, about -5% per decade. In the lower troposphere, however, the values are very different although they remain positive. Thus, there is evidence to suggest the existence of overall negative trends at layers 3A and 3B, and perhaps also at 2B and 4A. (World Meteorological Organization, 1986).

The results for the troposphere have recently been examined by Logan (1985) and her analysis indicates that the surface ozone at mid-latitudes displays two modes of seasonal behavior: a broad summer maximum within a few hundred kilometers of populated and industrialized regions in Europe and the United States; and a summer maximum in sparsely populated regions remote from industrial activity, in Canada and Tasmania, for example. She argues, in addition, that the current data base for different regions, in combination with limited historical data indicates that summertime concentrations of ozone near the surface in rural areas of Europe and the central and eastern U.S. may have increased by approximately 10-20 ppb (30-100%) since the 1940's. The seasonal cycle of ozone in the middle troposphere over Europe, the United States, and northern Japan is very similar to that at the surface, with a summer maximum, but it is quite different from that at 300 mb, which is characterized by a maximum in spring. There is good evidence for an increase in ozone in the middle troposphere over Europe during the past 15 years, and weaker evidence for a similar increase over Northern America and Japan. From this she argues that the summer maximum in ozone and the observed trends are due to photochemical production associated with anthropogenic emissions of NOx hydrocarbons and CO

EXHIBIT 5-64

Ozone Trend Estimates (% Per Year) As Determined from Balloon Ozonesondes Versus Those Determined from Dobson Measurements (Tiao, et al., personal communication)

Station	Ozonesonde		Total Ozone Readings on Sonde File
Aspendale (6/65-5/82, Brewer)	-.115 (.055)		-.162 (.075)
Biscarrosse (3/76-1/83, Brewer)	-.416 (.114)		-.587 (.185)
Hohenpeissenberg (1/70-2/83, Brewer)	-.174 (.052)		-.220 (.088)
Lindenberg (1/75-2/83, Brewer)	-.287 (.128)		-.269 (.266)
Payerne (9/68-12/81, Brewer)	-.149 (.045)		-.181 (.074)
Kagoshima (1/70-12/82, ECC)	.136 (.090)		.215 (.155)
Tateno (3/68-12/82, ECC	.085 (.082)		-.055 (.094)
Sapporo (12/68-12/82, ECC)	.148 (.103)		.203 (.138)
Wallops, Isl. (5/70-4/82, ECC)	.034 (.075)		.037 (.122)
Churchill (10/73-1/83, Brewer/ECC 9/79)	.473* (.118)	-.310** (.197)	.282 (.234)
Edmonton (10/70-12/82, Brewer/ECC 9/79)	.405* (.095)	.027** (.152)	.360 (.149)

EXHIBIT 5-64 (Continued)

Ozone Trend Estimates (% Per Year) As Determined from Balloon Ozonesondes Versus Those Determined from Dobson Measurements (Tiao, et al., personal communication)

Station	Ozonesonde		Total Ozone Readings on Sonde File
Goose Bay	.029*	-.095**	-.123
(6/69-12/82, Brewer/ECC 12/80)	(.060)	(.077)	(.099)
Resolute	-.194*	-.240**	-1.64
(1/66-1/83, Brewer/ECC 12/79)	(.045)	(.070)	(.074)

* Without intervention adjustment.

** With intervention adjustment.

Source: World Meteorological Organization (1986).

from combustion of fossil fuels. A strong seasonal variation in ozone observed at Natal, Brazil (6°S) may also result from emissions of NOx and hydrocarbons, in this case from agricultural burning. Maximum concentrations at Natal are similar to values found at mid-latitudes in summer. (World Meteorological Organization, 1986).

With the limited network of ozonesonde stations, however, the question remains as to whether the tropospheric ozone increase is due to local pollution effects or is symptomatic of a more general atmospheric behavior. (World Meteorological Organization, 1986).

Ground-Based and Satellite Data for Antarctica

Recently, Farman et al. (1985) have published the data, displayed in [Exhibit 5-65], **showing a large secular decrease in total ozone for the month of October over their station at Halley Bay, Antarctica [76 degrees south]. Since 1957 the mean total ozone for the month of October over Halley Bay has decreased by about 40 percent** with most of the decrease occurring since the mid-1970's. Since 1978, **satellite data from the Nimbus & TOMS and SBUV instruments confirm these findings.** Along with data in the early 1970's from the Nimbus 4 BUV instrument, the satellites show that in the southern hemisphere total ozone is generally at minimum during the springtime over the Antarctic continent (or generally poleward of about 70 degrees south). This minimum is surrounded by a range of maximum total ozone values centered at about 55 degrees south. The surrounding maximum region displays significant wave structure. The minimum often becomes distorted into an oblong shape and rotates along with the maximum. Exhibit 5-66 shows a twelve day sequence for October of 1984 which displays a 7 day rotation period. There is a marked tendency for the minimum to be displaced off the pole towards the direction of Halley Bay (World Meteorological Organization 1986).

Since 1979, the Nimbus 7 data show decreases in both the maximum and minimum region. The largest decreases (of order 40 percent) are in the minimum region leading to the lowest total ozone values ever recorded (less than 150 milli-atmosphere-centimeters -- Dobson units). Exhibit 5-67 (taken from Stolarski, et al., 1986) shows a map of the mean total ozone for each of the 7 Octobers measured by the TOMS instrument. The map is a polar projection with the outer edge at 30 degrees south latitude (Stolarski et al. 1986).

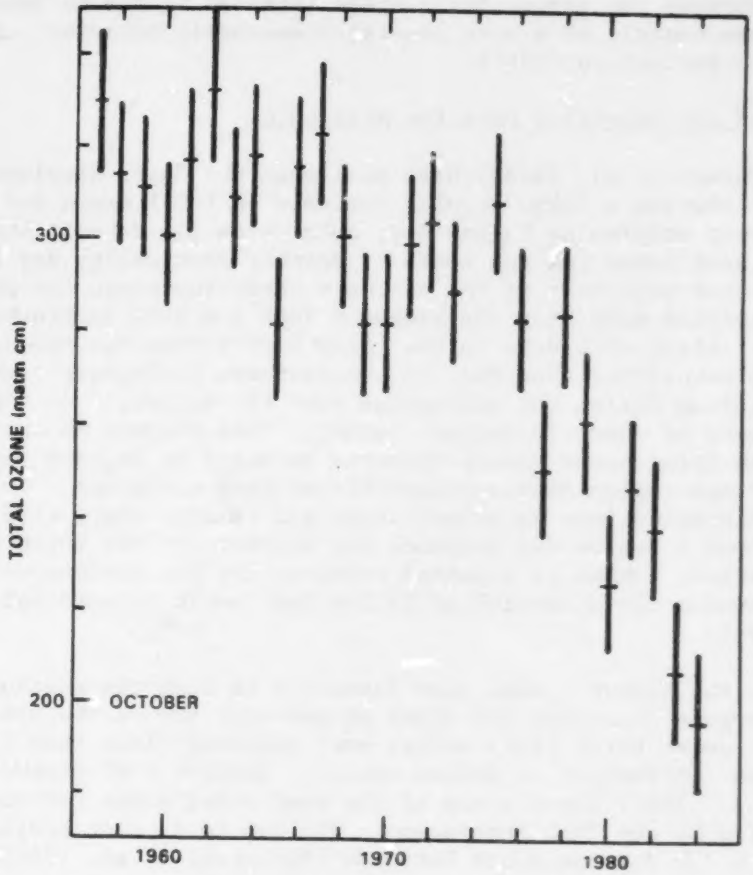
The other major feature of the data is the seasonal variation of the ozone minimum. The minimum values of total ozone appear in the spring, after the long polar night, at approximately the values entering the polar night. The rapid decline then takes place during September with the minimum being reached in October and a rapid recovery in November when the polar vortex breaks down (Stolarski, et al., 1986). **These data indicate that some mechanisms or mechanisms are at work in the cold southern polar night or twilight that are not generally included in models. This clearly warrants further investigation (World Meteorological Organization, 1986).**

Alternate Hypotheses of Antarctic Depletion

Explanation of the Antarctic ozone phenomenon still remain in the category of hypotheses. Many interesting ideas have been put forward which are, in principle, capable of explaining parts of the observed phenomena. Further data

EXHIBIT 5-65

Monthly Means of Total Ozone at Halley Bay

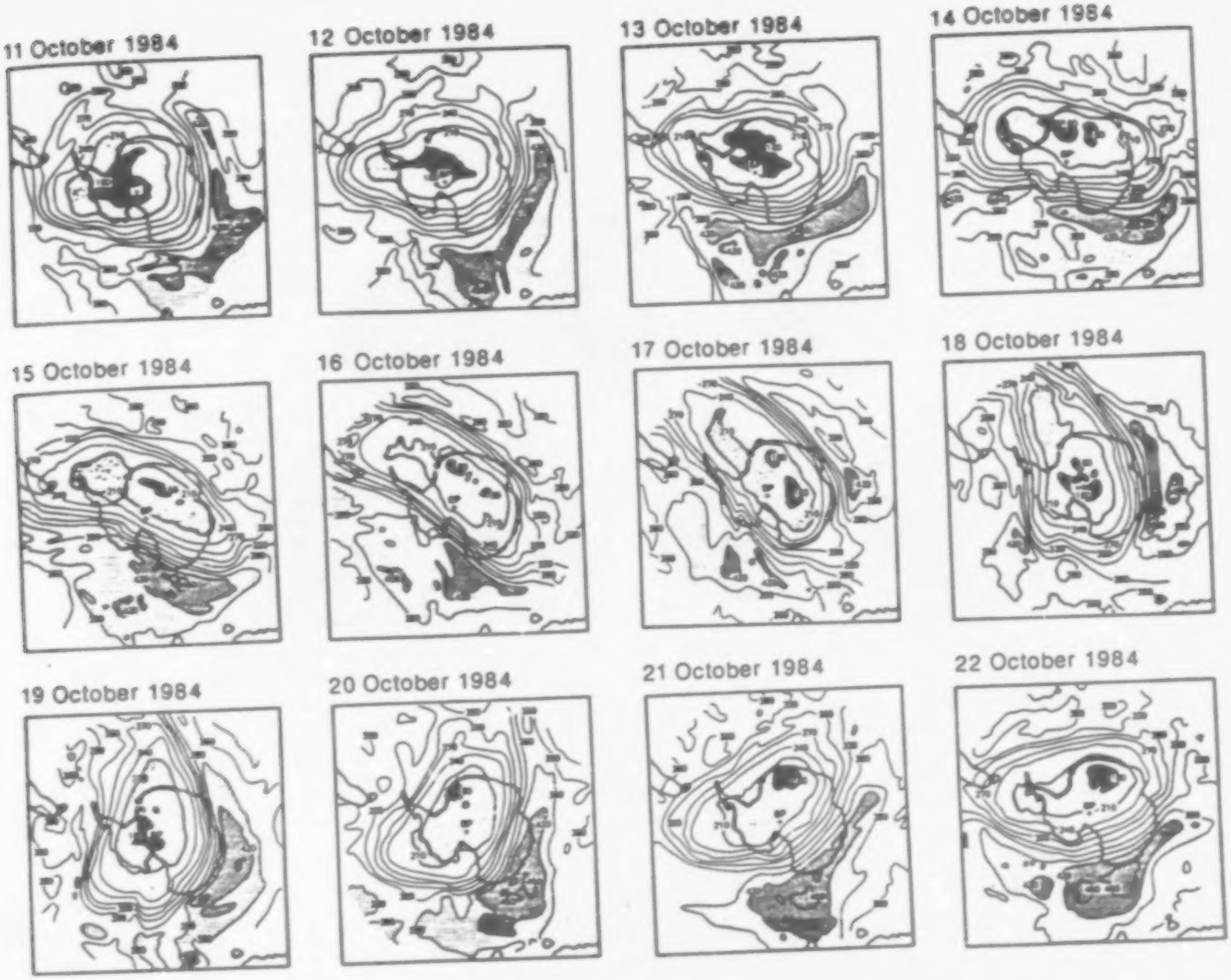


Total Ozone above Halley Bay in October for the years 1957 to 1984.

Source: World Meteorological Organization, (1986).

EXHIBIT 5-66

Nimbus 7 Antarctic Ozone Measurements: 12 Day Sequence

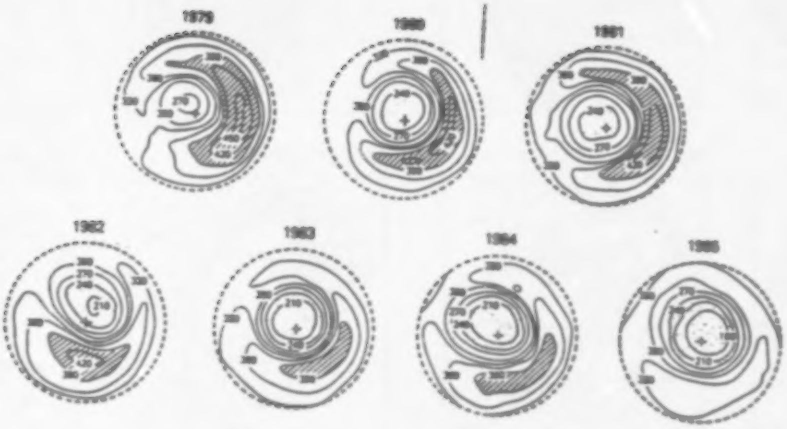

11 October 1984
12 October 1984
13 October 1984
14 October 1984
15 October 1984
16 October 1984
17 October 1984
18 October 1984
19 October 1984
20 October 1984
21 October 1984
22 October 1984

"Twelve-day sequence (11-22 October 1984) of TOMS measurements of total ozone content. The data are shown in south polar projections, with the pole indicated by a cross (SP) and Halley Bay shown by an asterisk. Contours are every 30 Dobson units (1 DU = 10^{-3} atm cm). The region shown extends to ~45° latitude and the Greenwich meridian is towards the top of each diagram. Shaded regions indicate total ozone values <180 and 210 DU and >390 and 420 DU."

Source: Stolarski et al. (1986)

EXHIBIT 5-67

Antarctic Ozone Measurements: Mean Total Ozone in October



"Six-year sequence of October monthly means of total ozone. South polar projections, with the pole indicated by a cross and 30°S latitude by a dashed circle. The Greenwich meridian is towards the tope of each panel. Contours are every 30 DU. The shaded regions indicate monthly mean total ozone amounts of <240 and >390 DU."

Source: Stolarski et al. (1986).

are clearly necessary to differentiate among competing ideas before a scientific consensus can be reached on the cause of the changes. The first concept put forward was that the decrease was caused chemically by the action of chlorine which is known to have increased due to chlorofluorocarbon release (Farman et al. 1985; Solomon et al. 1986; McElroy et al. 1986). For this explanation to work, the cold polar night and the polar stratospheric clouds must be invoked to modify the previously known chemistry in a major way. The rate limiting radical, ClO, must be present in the part per billion range (almost 100 times what would have been assumed based on previously known chemistry) in the lower stratosphere during September and October. Bromine has also been introduced as a possible enhancement for the chlorine theory. The chlorine theory is susceptible to test by the microwave instrument which is in place at McMurdo in the spring of 1986. The primary aspect of this hypothesis is that the driving force, chlorine chemistry, has a known secular variation.

Another primarily chemical hypothesis is that the depletion is due to nitrogen oxide (NOx) chemistry which is varying due to solar cycle variations in the production of Nox in the thermosphere. This idea requires the transport of this excess NOx downward such that polar night and twilight values are increasing to show a maximum a number of years after solar maximum. For this idea to work, NOx would have to be high, ClO normal, and the effect should show an 11 year cycle. Thus the major problem is the lack of an apparent cyclic behavior in the Halley Bay data.

A third class of hypotheses is that the depletion is caused primarily by a modification of the climatological pattern of the wind fields in the southern hemisphere. One suggestion is that increased aerosols from the El Chichon eruption and their associated stratospheric heating lead to lifting of the atmosphere and low total ozone values (Tung et al., 1986). Analysis of the data indicates that there are variations that exist that are superimposed on the secular decrease. These year-to-year differences may be due to variations in atmospheric dynamics. Furthermore, secular decrease in Antarctic stratospheric temperature has accompanied the ozone decrease. Present understanding would seem to indicate that these are not a result of the ozone decrease. Thus, it is possible that a secular change in the climatology of the south polar region is taking place. A test of these ideas would be that the chemistry would be relatively normal but analyses of temperature and constituent data should clearly show effects of modifications in transport properties. The primary problem with this hypothesis is to trace such modifications back to a cause that shows an apparent secular variation of the time period under consideration.

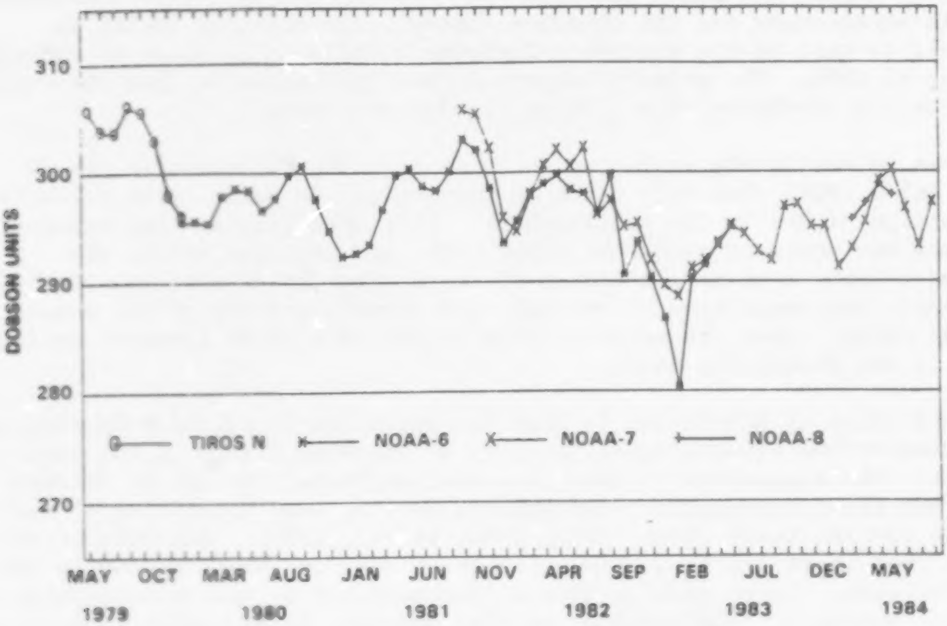
Several satellite systems, Firos, Nimbus 7, and NOAA9, exist for measuring column ozone at different latitudes and global ozone. The TOVS system on Tiros, and TOMS and SBUV-2 on Nimbus 7 and SBUV on the NOAA series. SBUV-2 can also measure ozone at various altitudes.

All satellite systems rely on interpreting irradiances as ozone and require corrections for aerosols and instrument drift. Thus, the major problem in determining ozone trends from these instruments is maintaining the calibration of the systems.

Exhibit 5-68 shows global ozone measurements for the TOVS.

EXHIBIT 5-68

Global (60°N-60°S) Monthly Total Ozone
Determined from NOAA TOVS System



Ozone trend estimates shown for global scale.

Source: World Meteorological Organization (1986).

The main problem in this system is that the TOVS system requires regression against the ground-based Dobson network. These data seem to indicate a drop in ozone, perhaps attributable to El Chichon. The data record is too short to determine if the trend is a short-term fluctuation or part of a longer trend.

Nimbus 7 Results

Results from Heath's analysis of Nimbus 7 have not yet been published, but results have been mentioned by NASA at Senate hearings and shown at several meetings.

Heath shows a .56 ± 19 percent per year global ozone decline from 1978 to 1984 (Heath, personal communication). Heath's interpretation of this trend is qualitatively consistent with seasonal and latitudinal predictions in Isaksen's two-dimensional time-dependent runs, although of greater magnitude. Exhibit 5-69 shows the 1978 to 1984 estimates of depletion from Isaksen's model and according to Heath's interpretation of the Nimbus 7 data. Clearly the pattern is similar, although Heath's interpretation of the satellite data suggests depletion eight times greater at 80°N than Isaksen's model. Isaksen's estimates of Antarctic ozone (without special chemistry), however, are smaller than Arctic estimates, contrary to Heath's data.

One problem with interpreting data is the shortness of the satellite data. It is not clear whether these "trends" are long-term in nature, or short-term fluctuations. Additional analysis is needed and 1985 and 1986 is needed quickly.

Use of Antarctic and Satellite Measurements in Risk Assessments

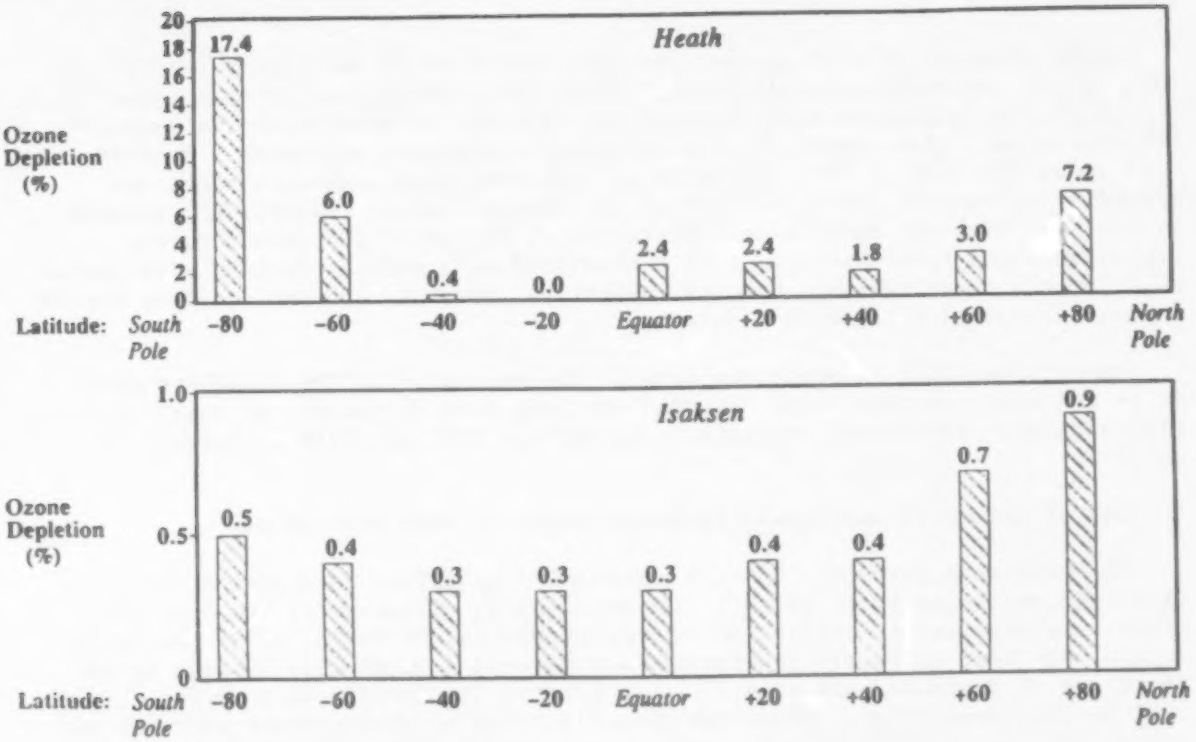
The published Antarctic and yet unpublished satellite data present a difficult challenge to us in this risk assessment. Clearly, if the Antarctic trends are chemical in origin and extrapolatable to the world, or if the Nimbus 7 data have been correctly interpreted and portend a chemically induced trend, the risks of depletion are significantly greater than predicted in models being used in this assessment. Given the disequilibrium between current emission and concentrations of CFCs, if these results portend the future, depletion can be expected to increase with a large cutback in depleting chemicals.

In our judgment, however, it is premature to reach the conclusion that these observations can be used for assessing global trends. The scientific analysis to support such a judgment is incomplete. Until the analysis reaches the stage where the Antarctic situation can be extrapolated to the rest of the world or until the Nimbus 7 data is shown to be real and representative of the rates of depletion in the future, these data should be treated with caution. Thus, for decisionmaking purposes we propose that current models be considered the appropriate tools for assessing future risks.

The satellite and ground-based Antarctic data do, however, raise a "blinking yellow alert," which may require reassessment of risks. Because both sets of data present sufficiently stark pictures of a possible future efforts need to be made on an expedited basis to better resolve our understanding of these data sets. The Nimbus 7 data, already global in character, need the earliest analysis so that resolution of its implications can be reached. In particular,

EXHIBIT 5-69

Preliminary Ozone Trend Data (Heath versus 2-D Model Results) (Isaksen)



Predicted ozone changes from Isaksen's 2-D model are qualitatively consistent with preliminary data from Heath.

Source: Heath (personal communication); and Isaksen and Stordal (1986).

a very strong effort must be made to expedite the flow of data from satellites to analysis to peer review. The flow of data must be as close to "real time" as possible, not a year or two behind.

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